Energy Research and Development Division
FINAL PROJECT REPORT

Laboratory Testing and Field Measurement of Plug-in Electric Vehicle (PEV) Grid Impacts

Appendix H

Prepared for: California Energy Commission
Prepared by: San Diego Gas & Electric and Quanta Technology

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APPENDIX H:
Grid Impact Testing and Data Analysis

Grid Impact Testing and Data Analysis

Tasks 2.5 & 2.6 Report: Real Time Digital Simulator (RTDS) Testing of Impacts of Increased PEV Penetration on Distribution Systems

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Confidentiality Note

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1 Introduction and Modeling

This report provides the test results of investigating the impact of the increase in penetration of PEV (and the corresponding increase in charging demand) on the distribution systems, including service transformers, circuit devices and voltage/power flow profiles of the circuits. A representative circuit layout, used in the study, is shown in *Figure 1*.

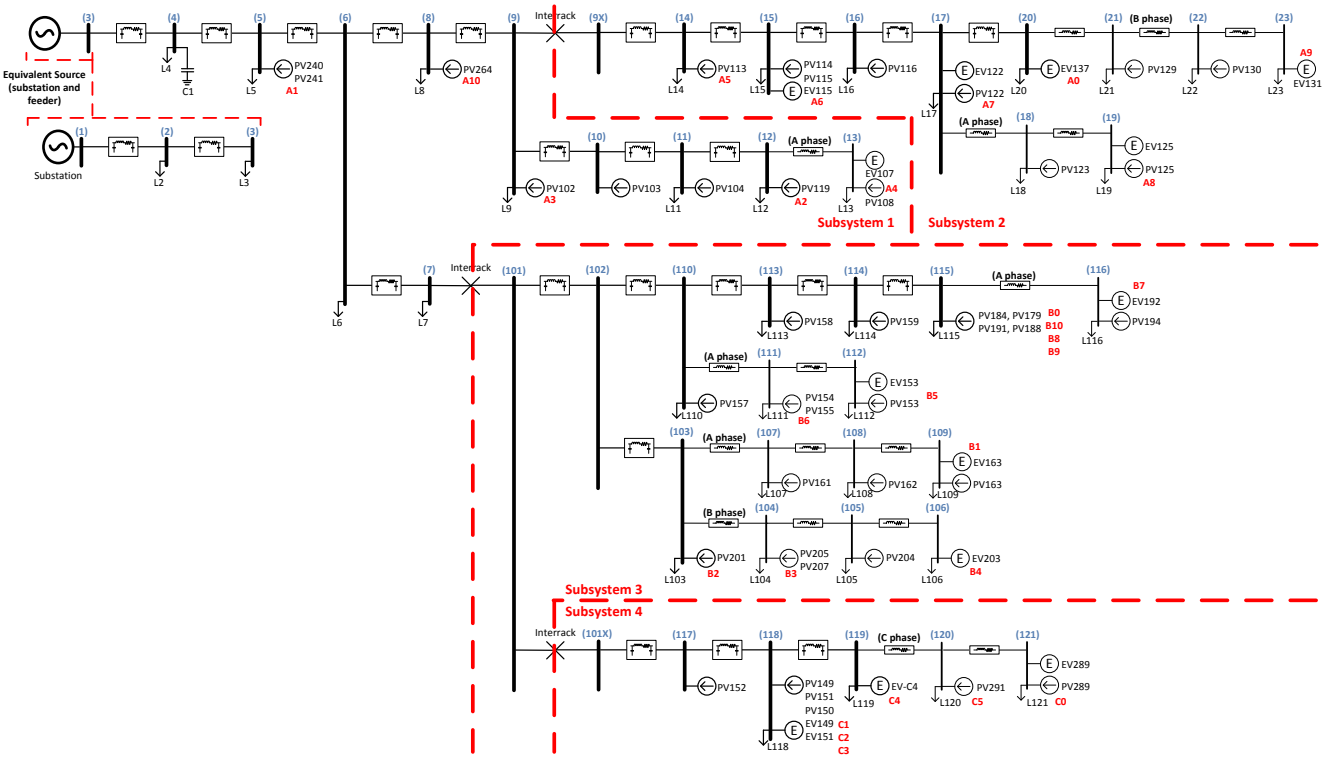

Figure 1 – Test Circuit Layout

Two types of PEV chargers were investigated:

- AC Level 2 charger at 240V (up to 9.8kW)
- DC fast charger (up to 40kW).

Residential EV chargers were represented by the AC 240V model and comprise the bulk of this study. The DC fast chargers were tested at two locations: Bus 5 representing a shopping mall, and Bus 118 representing a school, as candidate locations for future deployment of DC fast chargers.

The circuit under study had multiple PEV customers, as well as several solar PV inverter installations (roof-top PV). The loads, PV, and EV units were modeled on a secondary low voltage (240V) circuit, connected between phases through two 12.47kV-to-0.120kV windings. PV and EV were represented by current sources connected between the two windings (240V) and loads were connected phase to ground (120V). For single phase loads, only a single 12.47kV-to-0.24kV service transformer was used. Transformer impedances were set to Z = 2.5% with X/R ratio of 15.

The load exceeded the transformer kVA rating at numerous secondary locations due to the load lumping methodology used to model the circuit in RTDS – not every secondary location on the circuit was modeled. The secondary circuit locations which featured existing PV or EV systems, or for which had strong potential for the addition of PV or EV systems, were given priority for explicit modeling. The loads along the circuit were lumped into the secondary circuit transformers at the defined buses. For the cases where the lumped load greatly exceeded the transformer rating, the loads were split so that a portion would remain on the high voltage (primary) side of the transformer, reducing the actual kVA through the transformer to within rated values of transformers. A typical representation of a secondary circuit is shown in *Figure 2*.

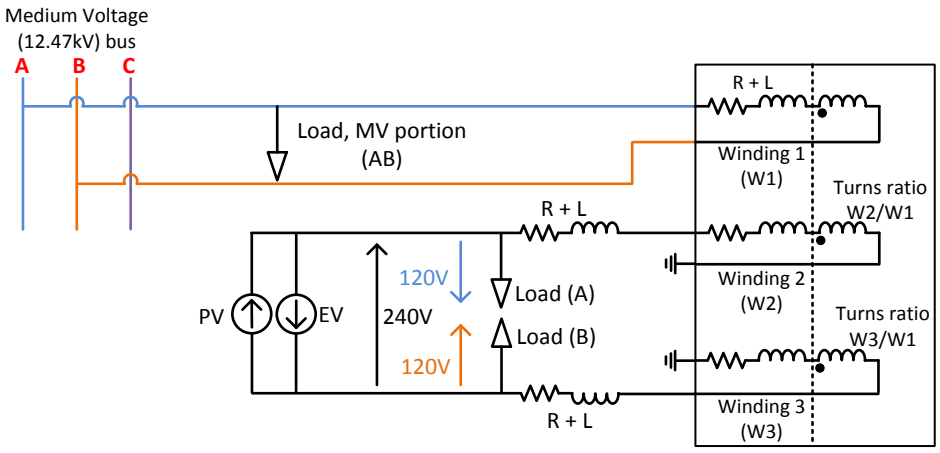

Figure 2 – Low voltage (240V) secondary circuit

Circuit A was modeled with 28 secondary circuits, 14 of which had existing EV customers.

Two sets of EV customer sizes were chosen for the study, one with completely random distribution, and one with random distribution with a set percentage of each size:

- Set 1: Random distribution of 3.3kV, 5.8kV, 6.6kV, and 9.8kV EV sizes
- Set 2: 4x 3.5kV (~28%), 8x 6.8kV (~58%), 2x 9.8kV (~14%)

Three sets of EV charging times were selected, with random distribution between specified start and end times:

- Always On: EV was charged from 16:00 (4:00pm) through to 4:00 (4:00am) the next morning
- Uncontrolled Operation: Start times from 16:00 (4:00 pm) to 18:00 (6:00 pm), end times range from 22:00 (10:00 pm) to 4:00 am the next morning
- Controlled Operation: Start times from 21:00 (9:00 pm) to 24:00 (12:00 am), end times from 3:00 am to 6:00 am the next morning

In addition to the fourteen (14) existing customers with EV, values were assigned for all secondary circuits to simulate the case that all transformers would feature EV charging. Customer loads, number of PEVs and PV sizes in the circuit are given in ***Table 1*** and ***Table 2***. The existing EV customers are shaded in the tables.

Table 1 – RTDS Transformer, Load, PV, and EV Parameters (Subsystem 1 and 2)

	Transformer Parameters			Load and PV			EV Size		EV Charging Time			
Bus #	XFMR kVA		Connection	Total Load		Total PV	Set 1	Set 2	Uncontrolled Charging		Controlled Charging	
	Rated	Actual		kW	kVAR	kW	kW	kW	Start	End	Start	End
2			ABC	170	23							
3			ABC	269	34							
4			ABC	146	90							
5			ABC	587	102	30.9						
6			ABC	810	139							
7			ABC	191	32							
8			ABC	267	46	7.3						
9			ABC	100	19	3.5						
10	50	70	A	55	9	5.9	9.8	3.5	17:00	01:30	21:30	04:00
11	50	35	C	28	4	4.6	6.6	6.8	17:00	00:30	23:30	03:00
12			BC	126	22	3.5						
13	100	88	A	69	12	9.8	3.3	3.5	16:30	22:30	23:00	05:00
14			ABC	446	77	3.9						
15	50	41	AB	55	10	12.7	3.3	6.8	16:00	00:30	21:00	04:30
16	50	41		56	9	5.0	5.8	9.8	17:00	01:00	00:00	03:00
17	50	41	AB	55	9	6.0	5.8	3.5	16:30	23:30	23:30	03:00
20	100	82	AC	235	41		6.6	6.8	18:00	01:00	21:00	05:00
21	100	89	B	70	12	4.7	5.8	6.8	16:30	03:00	23:00	05:00
22	25	16	B	14	3	3.3	9.8	3.5	16:30	03:00	21:30	06:00
23	25	18	B	14	2		3.3	6.8	17:00	22:30	22:00	03:00
18	50	35	A	28	5	1.5	3.3	6.8	16:00	22:00	22:00	03:30
19	50	32	A	41	7	3.3	5.8	9.8	16:30	23:30	23:30	05:00

Table 2 – RTDS Transformer, Load, PV, and EV Parameters (Subsystem 3 and 4)

	Transformer Parameters			Load		PV	EV Size		EV Charging Time			
Bus #	XFMR kVA		Connection	Total Load		Total PV	Set 1	Set 2	Uncontrolled Charging		Controlled Charging	
	Rated	Actual		kW	kVAR	kW	kW	kW	Start	End	Start	End
110			ABC	57	9	3.7						
113	50	35	C	28	5	27.5	6.6	6.8	16:00	02:00	00:00	04:30
114	50	36	B	29	6	5.0	5.8	6.8	16:30	01:30	23:30	05:00
115			ABC	579	99	14.1						
116	100	82	A	137	24	13.2	6.6	3.5	17:30	23:30	21:00	05:30
111	100	108	B	84	14	4.6	5.8	6.8	16:00	23:00	22:00	03:00
112	50	35	B	28	5	4.7	5.8	6.8	17:30	02:30	21:30	05:00
103			ABC	294	51	11.6						
107	50	52	A	41	7	5.2	5.8	3.5	17:30	00:00	00:00	04:00
108	50	52	A	41	7	4.9	6.6	6.8	18:00	03:00	21:00	05:00
109	50	35	A	28	5	4.3	9.8	6.8	17:30	22:30	22:30	06:00
104	100	89	B	70	12	10.9	9.8	9.8	17:00	02:30	21:00	03:30
105	50	35	B	28	5	5.2	5.8	3.5	18:00	23:30	23:30	05:30
106	25	17	B	14	2		9.8	9.8	17:00	00:30	23:30	05:00
117						2.9						
118A	50	41	AB	55	10	9.5	6.6	6.8	18:00	01:30	00:00	04:00
118B	50	46	BC	260	10	9.5	9.8	6.8	16:30	02:00	23:00	05:30
119	50	53	AB	42	7		6.6	3.5	17:30	04:00	00:00	03:00
120	25	24	C	19	3	5.1	9.8	6.8	17:30	00:30	00:00	05:30
121	25	24	C	19	3	5.4	5.8	6.8	16:00	02:30	22:00	03:30

The test system had the capability to select a starting time and ran through the charging profile, looping back to the beginning at 12:00 am, until it was commanded to stop. The PV output followed a high-fluctuation solar radiation profile which covered a complete day (24 hours). It was assumed that all PVs on the circuit were using the same profile. The PV outputs were scaled according to the profile shown in *Figure 3*. PV data was obtained from SDG&E's Solar Carport installation and corresponded to measurements for a selected day (July 9, 2013).

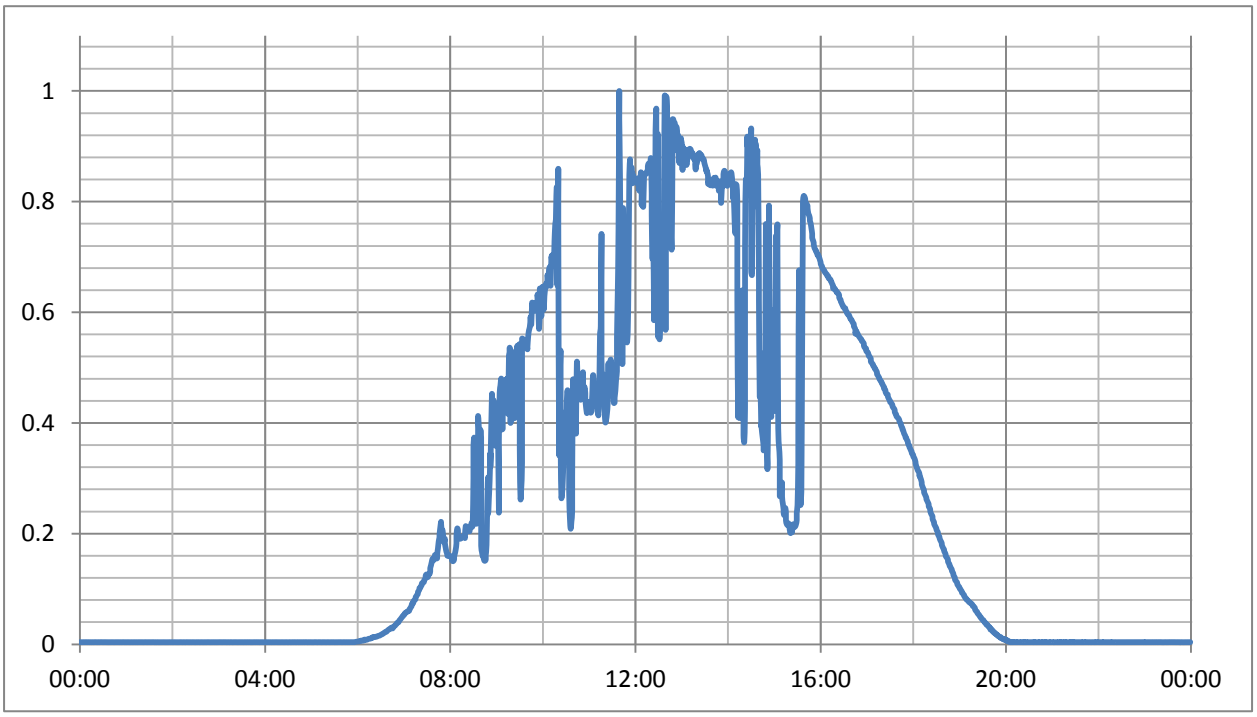

Figure 3 – 24-hour PV profile scaling

The loads were scaled according to a pre-programmed 24-hour profile, provided by SDG&E as a typical profile for the circuit under study. The load profile is shown in *Figure 4*.

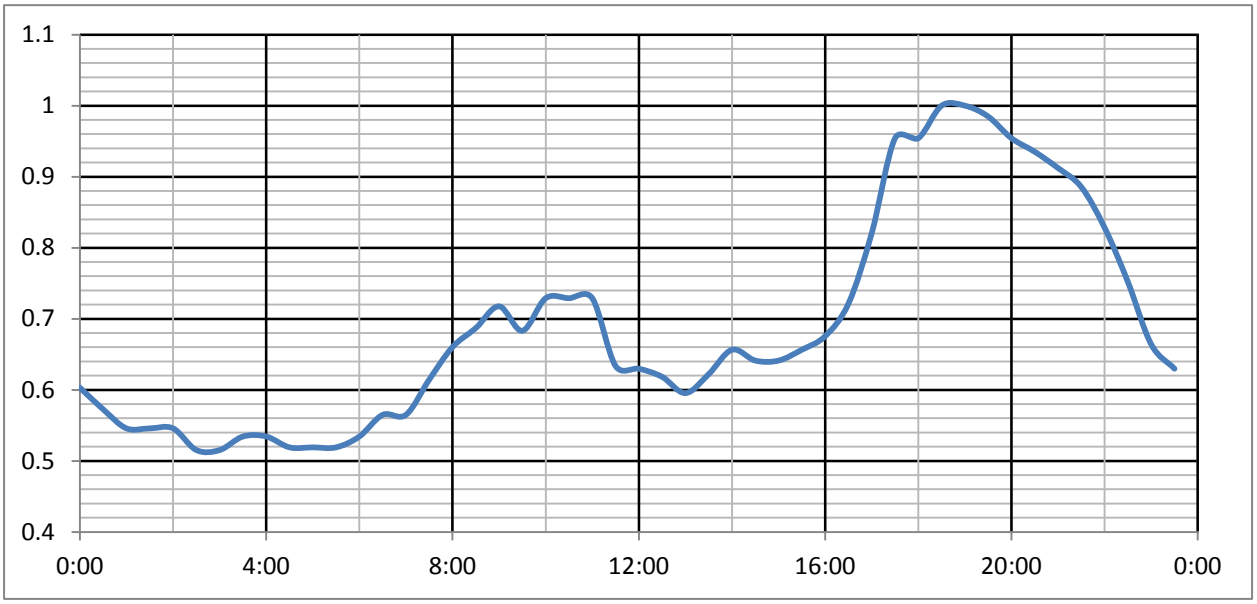

Figure 4 – 24-hour load profile scaling

The voltage at the beginning of the test circuit was adjusted individually for the three phases according to (1):

$$V(pu) = \frac{4\frac{S_{bus}}{S_{base}} + 121}{120} \quad (1)$$

Where:

S_{bus} = MVA at beginning of test system

S_{base} = 5.2MVA, apparent power flow into test system under full load condition

This was based on SDG&E's load tap changer (LTC) control strategy, which adjusted the voltage reference based on the circuit loading through the substation transformer. Because the first part of the circuit segments and some loads were lumped together, the voltage adjustment was applied per phase to account for the unbalanced voltage conditions downstream of the LTC point.

2 Proposed Test Plan

The test plan was divided into offline (RTDS only) and online (RTDS in conjunction with Grid and PEV simulators) sections.

2.1 *Offline tests*

The offline tests established a baseline performance of the modeled Circuit A in RTDS and verified the controls for load, PV, and residential EV operation. All test cases were run for a 24-hour loop in accelerated time, where 1-second real time was equivalent to 1-minute of simulation time. All relevant offline tests were conducted using EV Set 1 (random distribution), and either uncontrolled or controlled charging times. The proposed tests were:

- Baseline circuit performance with fixed maximum loads
- Circuit performance with varying loads and integration of PV
- Full system test with varying loads, PV output, and EV active with all existing customers
- Full system test with varying loads, PV output, and EV active on all transformer secondary circuits

2.2 *Online tests*

The online tests included the operation of the Grid and PEV simulations for use in conjunction with the RTDS in a closed loop. The RTDS sent voltage waveform data through its Analog Output to the Grid simulator. The Grid simulator in turn, amplified this signal and fed into the PEV simulator, replicating the 240V environment the PEV simulator would normally operate in. Finally, the PEV simulator generated a current signal and output to the RTDS, bringing the effect of the charging vehicle back into the computer (RTDS) model. The schematic diagram of the test setup is shown in *Figure 5*. Online tests included both cases run in real time and in 24-hour accelerated time (1 minute real time was equal to 1 hour simulation time). Online tests were conducted with both EV Set 1 (random distribution) and Set 2 (random distribution with set percentages of each PV size), and all sets of charging times.

The proposed tests were:

- Verify closed loop operation with RTDS
- Analyze circuit performance with varying loads and integration of PV
- Verify single EV operation
- Expand analysis to multiple EVs on a single transformer
- Run full system test with all existing EV customers
- Run full system test with EV active on all transformer secondary circuits

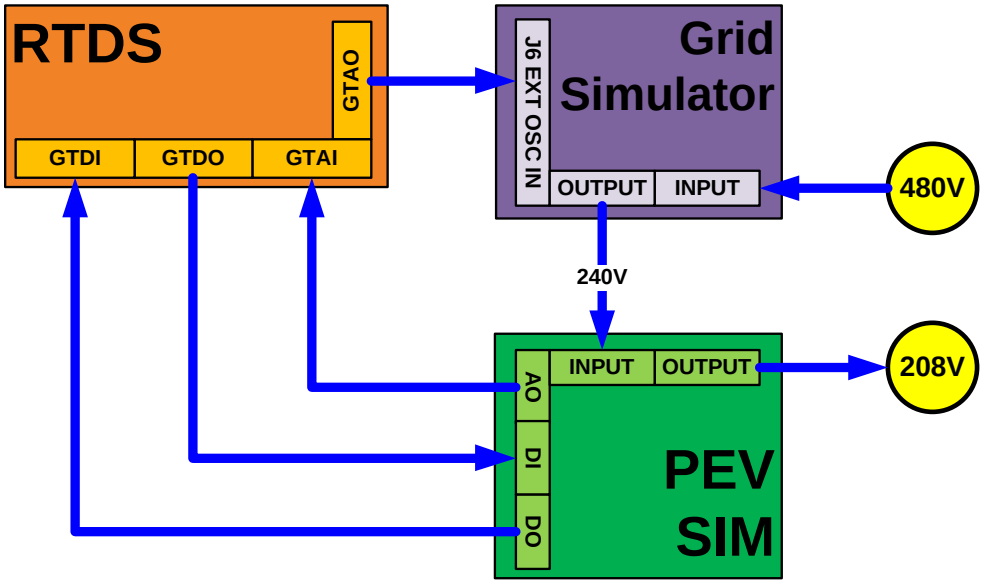

Figure 5 – RTDS hardware in loop setup for testing PEV charging impact

2.3 *Fast DC charger tests*

The DC charger tests comprised two cases at full power (40kW) for 20 minutes in accelerated time. Two different locations were selected, representing a fast charger at a shopping mall and a second fast charger at a school. The majority of the Circuit A area was comprised of residential houses that were expected to have level 2 chargers.

3 Test Results for PEV Impact Evaluation

3.1 *Offline – Baseline Test with Fixed Loads, No PV*

This test verified the accuracy of the integration of Circuit A model and secondary low-voltage (240V) circuit for the maximum load. No PV or EV outputs were integrated into the circuit in this test. The measured voltage, real power, and reactive powers of the modeled RTDS circuit were compared to their respective values from SynerGEE in ***Table 3***. It was seen that the maximum voltage deviation was less than 1%. The voltage profile of Circuit A is shown in *Figure 6*, with bus locations shown at proportional distances apart.

Table 3 – Comparison of V, P, and Q from RTDS to SynerGEE

SynerGEE and RTDS Comparison (VPQ)								
Bus	Miles	V3PH (pu)			P (kW)		Q (kVAR)	
		SynerGEE	RTDS	%error	SynerGEE	RTDS	SynerGEE	RTDS
4	4.195	1.021	1.022	0.1%	4609	4971	812	897
6 (to 8)	4.426	1.018	1.017	0.1%	1659	1687	287	301
6 (to 7)					1537	1867	265	328
9 (to 10)	4.716	1.016	1.015	0.1%	278	1028	47	186
9 (to 14)					1014	284	175	52
15	5.162	1.013	1.012	0.2%	513	523	88	99
17 (to 20)	5.518	1.012	1.011	0.2%	333	339	58	63
17 (to 18)					69	71	12	15
20	5.774	1.016	1.010	0.6%	98	100	17	24
22	6.067	1.016	1.014	0.2%	14	14	2	3
18	5.607	1.005	0.994	1.0%	41	42	7	9
10	4.807	1.016	1.014	0.1%	223	227	38	40
12	5.038	1.006	1.014	0.8%	69	72	12	15
				#DIV/0!				
101 (to 102)	4.563	1.018	1.016	0.1%	1346	1477	233	266
101 (to 117)					191	197	33	38
102 (to 110)	4.594	1.018	1.016	0.1%	942	955	162	171
102 (to 103)					404	522	70	95
110 (to 113)	4.655	1.016	1.016	0.0%	773	781	134	138
110 (to 111)					112	115	19	28
115	4.905	1.006	1.013	0.7%	137	141	24	30
111	4.703	1.020	1.020	0.1%	28	28	5	7
103 (to 107)	4.695	1.009	1.016	0.7%	110	114	19	24
103 (to 104)					112	114	19	27
108	4.871	1.009	1.001	0.7%	28	29	5	6
105	4.882	1.020	1.019	0.1%	14	14	2	3
118	4.901	1.018	1.016	0.2%	80	82	13	15
119	4.971	1.018	1.016	0.2%	38	38	6	9
120	5.109	1.022	1.025	0.3%	19	19	3	5

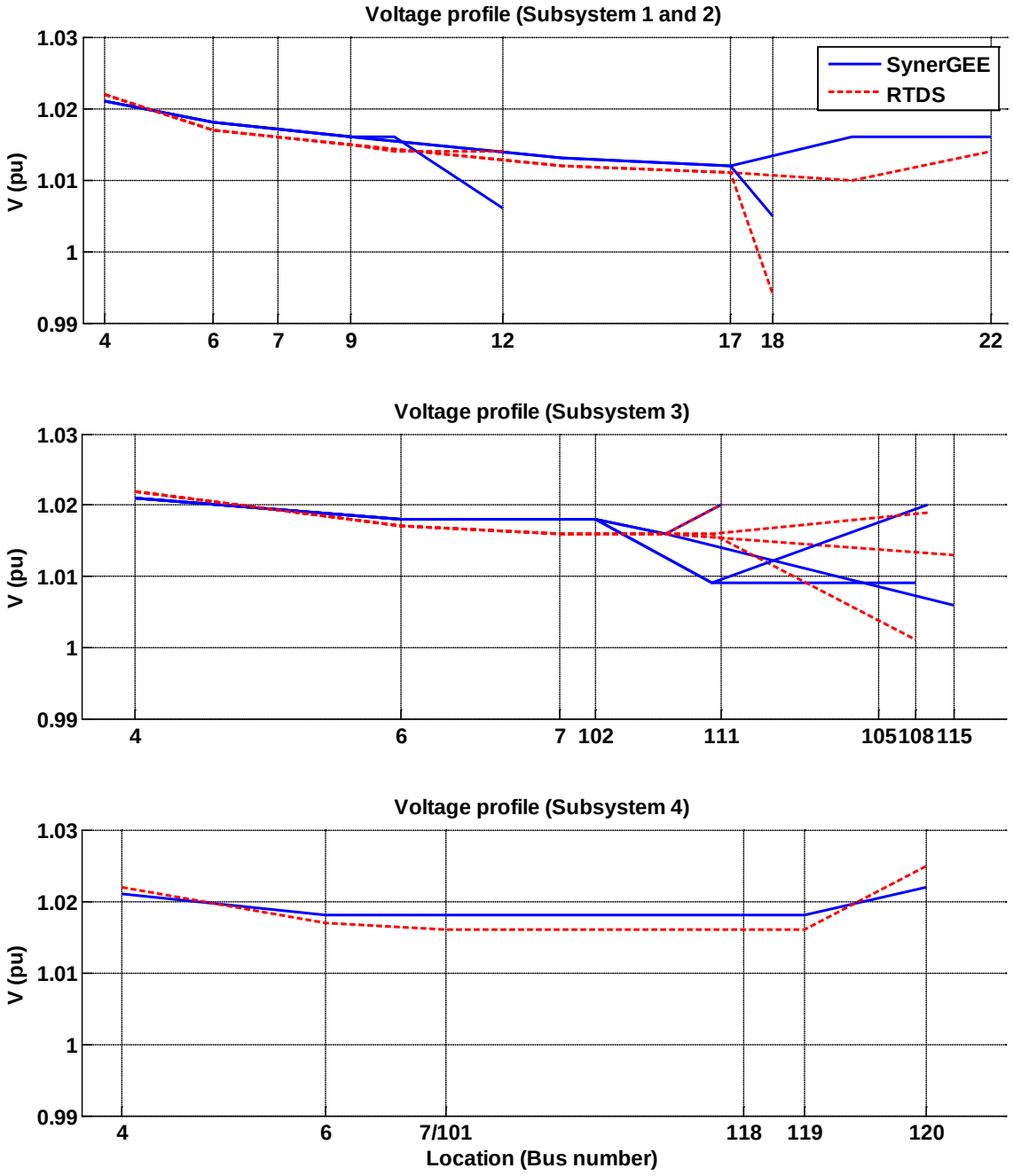

Figure 6 – Voltage profile for Circuit A for SynerGEE and RTDS

The measured kVA loading of the transformers and primary and secondary side voltages are shown in *Table 4*.

Table 4 – Transformer and secondary circuit parameters

Bus	Transformer kVA		Vp	Vs
	Rated	Actual	pu	pu
15	50	41	1.006	0.987
16	50	41	1.005	0.987
17	50	41	1.004	0.986
20	100	82	1.013	0.981
21	100	89	1.014	0.980
22	25	18	1.014	1.004
23	25	17	1.014	1.005
18	50	35	0.994	0.979
19	50	52	0.994	0.971
10	50	70	0.999	0.968
11	50	35	1.024	1.010
13	100	88	0.999	0.965
113	50	35	1.024	1.009
114	50	36	1.018	1.003
116	100	82	0.997	0.965
111	100	108	1.020	0.978
112	50	35	1.020	1.004
107	50	52	1.002	0.979
108	50	52	1.001	0.978
109	50	35	1.001	0.986
104	100	89	1.019	0.985
105	50	35	1.019	1.004
118A	50	41	1.010	0.994
118B	50	46	1.017	0.984
119	50	53	1.010	0.986
120	25	24	1.025	1.013
121	25	24	1.025	1.012

3.2 *Offline – Baseline Test with Variable Load and PV Profiles*

This test covered circuit performance for a 24-hour period (starting from 8:00am) with SDG&E provided load profile and a high fluctuation PV profile, shown in *Figure 3* and *Figure 4* respectively. The test was run in accelerated time, with one-second real time set equivalent to 1 minute of simulation time. The voltage at all selected circuit locations is shown in *Figure 7* along with the 24-hour load and PV profile. It was seen that voltage on the circuit varied from 0.97pu through 1.04pu, depending on location and loading. It was observed that the voltage characteristic was dominated by the varying load profile. The PV output fluctuation caused slight voltage variations during the day time. The impact on primary (12 kV level) voltages was minor, but sudden changes in the secondary voltages were seen in the profiles.

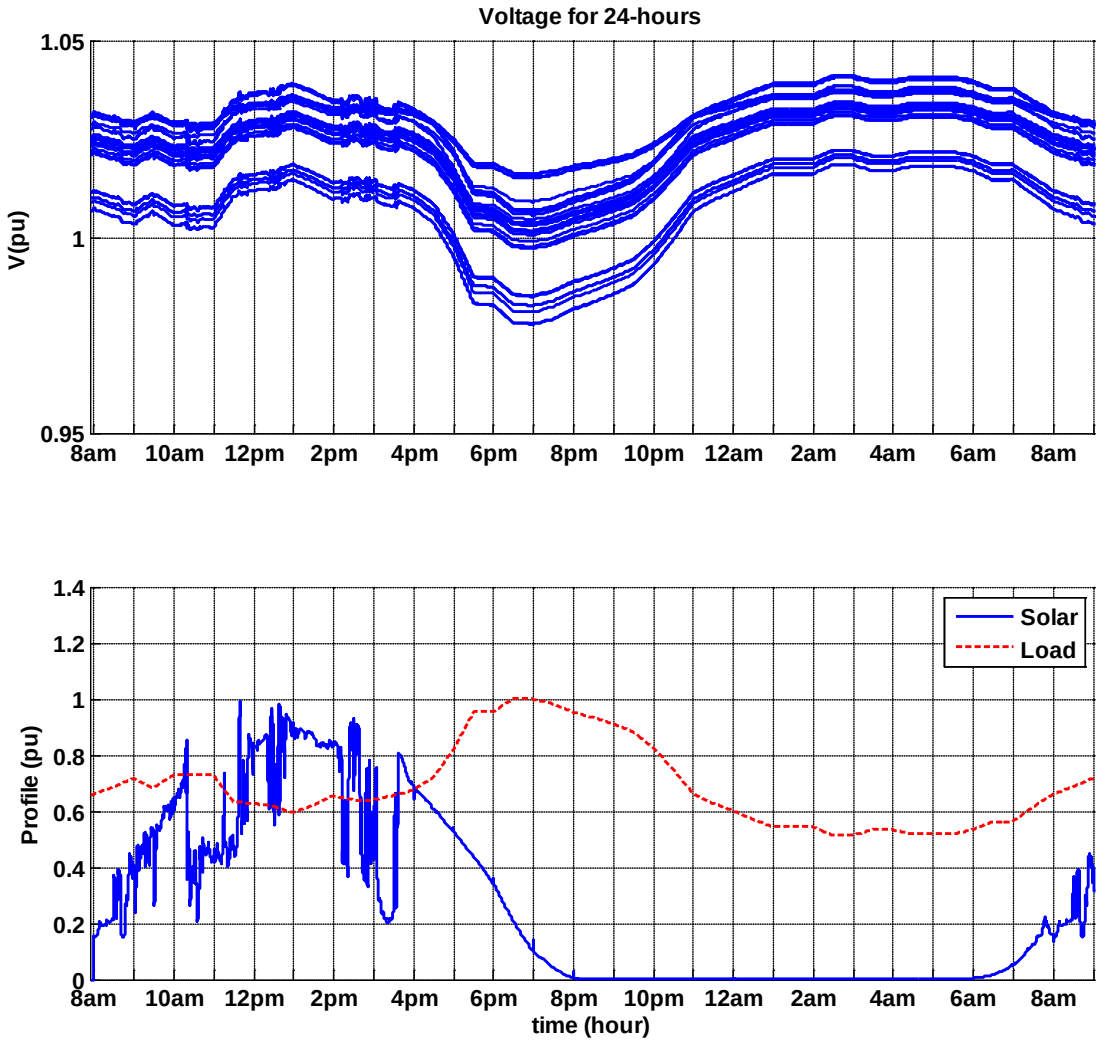

Figure 7 – Voltage at all circuit locations for varying load and PV profile

Voltages for selected locations on each subsystem are shown in *Figure 8*. Transformer voltages and currents are shown in *Figure 9*, *Figure 10*, *Figure 11*, and *Figure 12*.

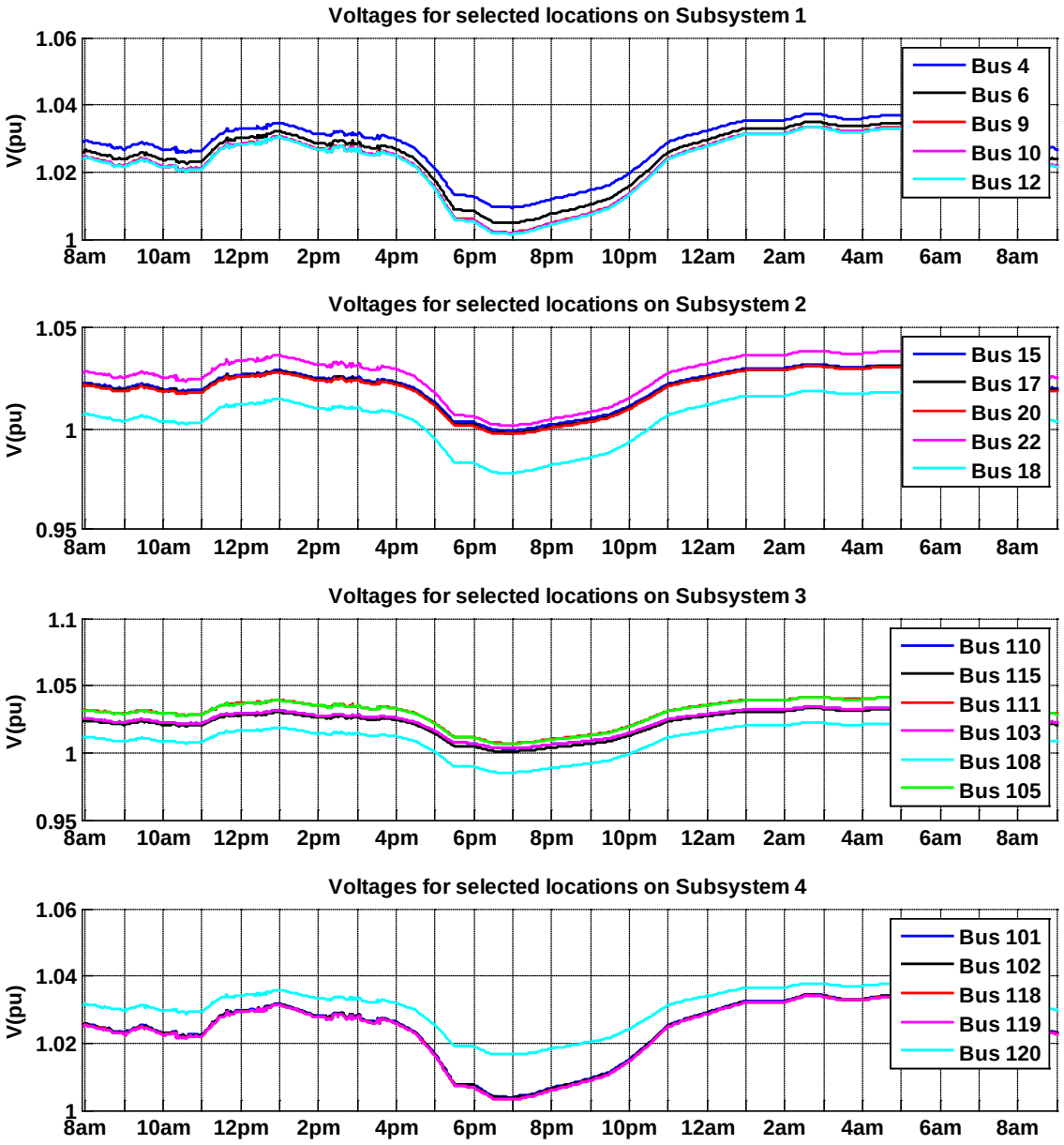

Figure 8 – Voltage at selected circuit locations for varying load and PV profile

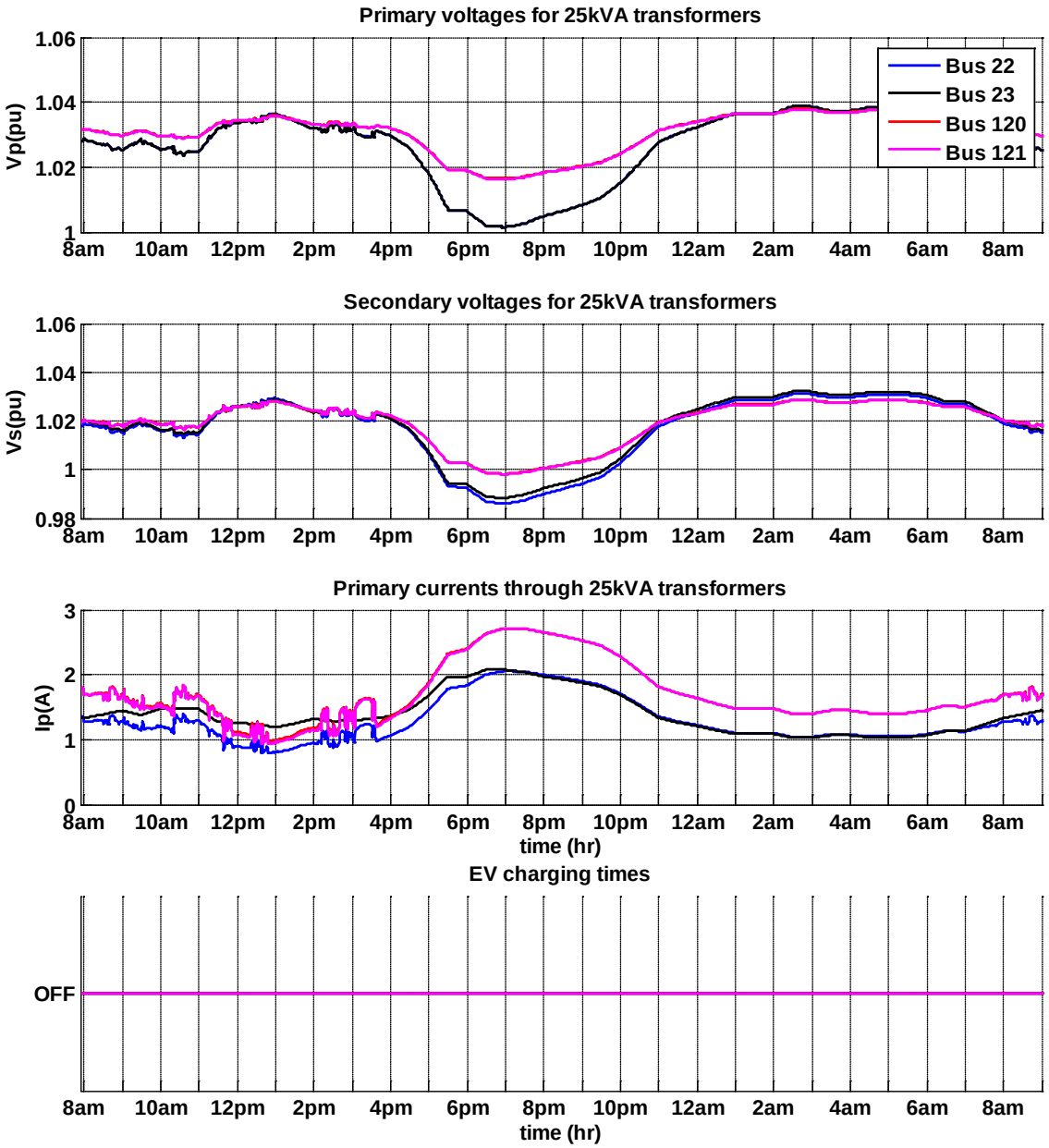

Figure 9 – Primary and secondary voltages and current at 25kVA transformers

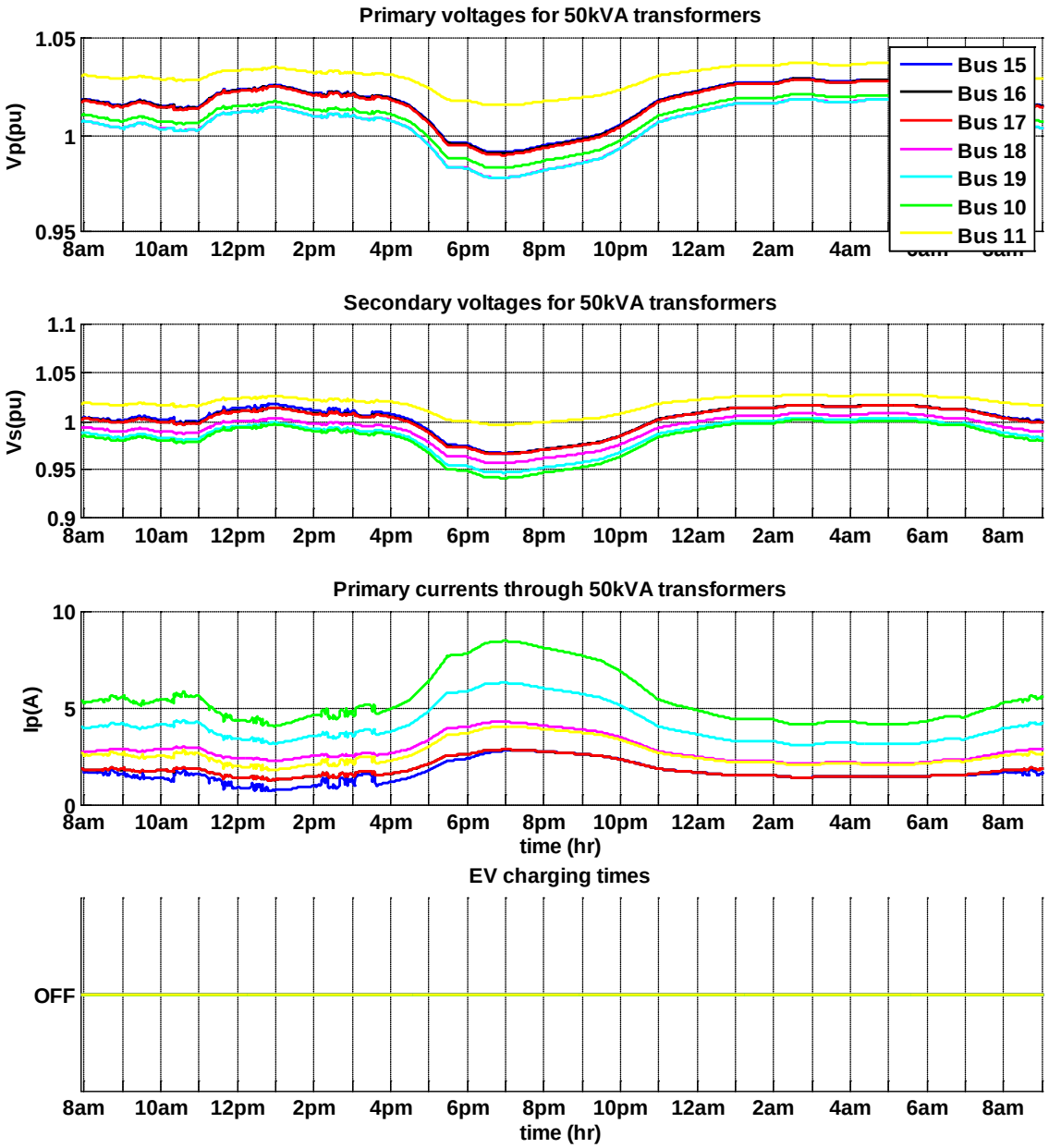

Figure 10 – Primary and secondary voltages and current at 50kVA transformers

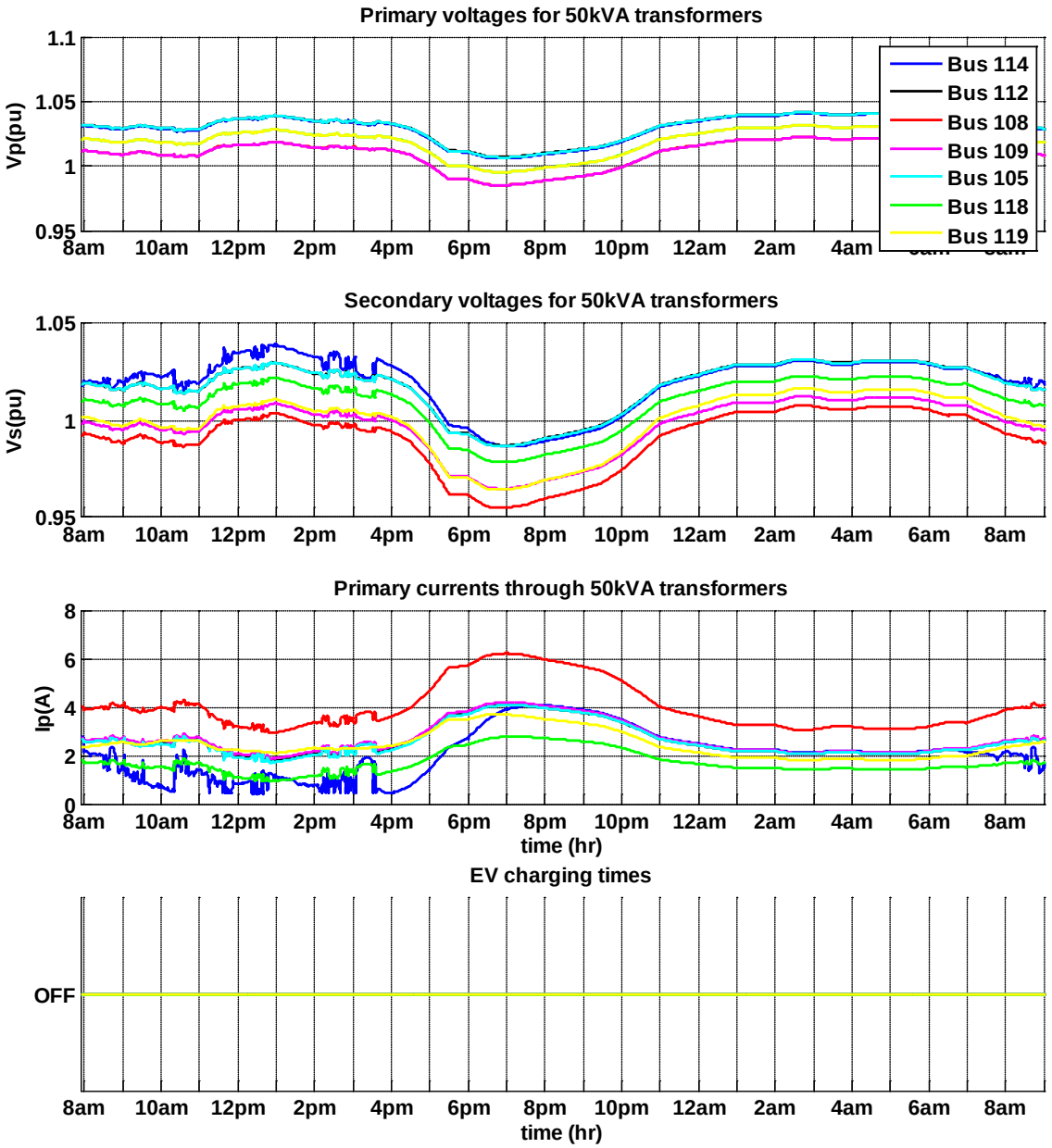

Figure 11 – Primary and secondary voltages and current at 50kVA transformers

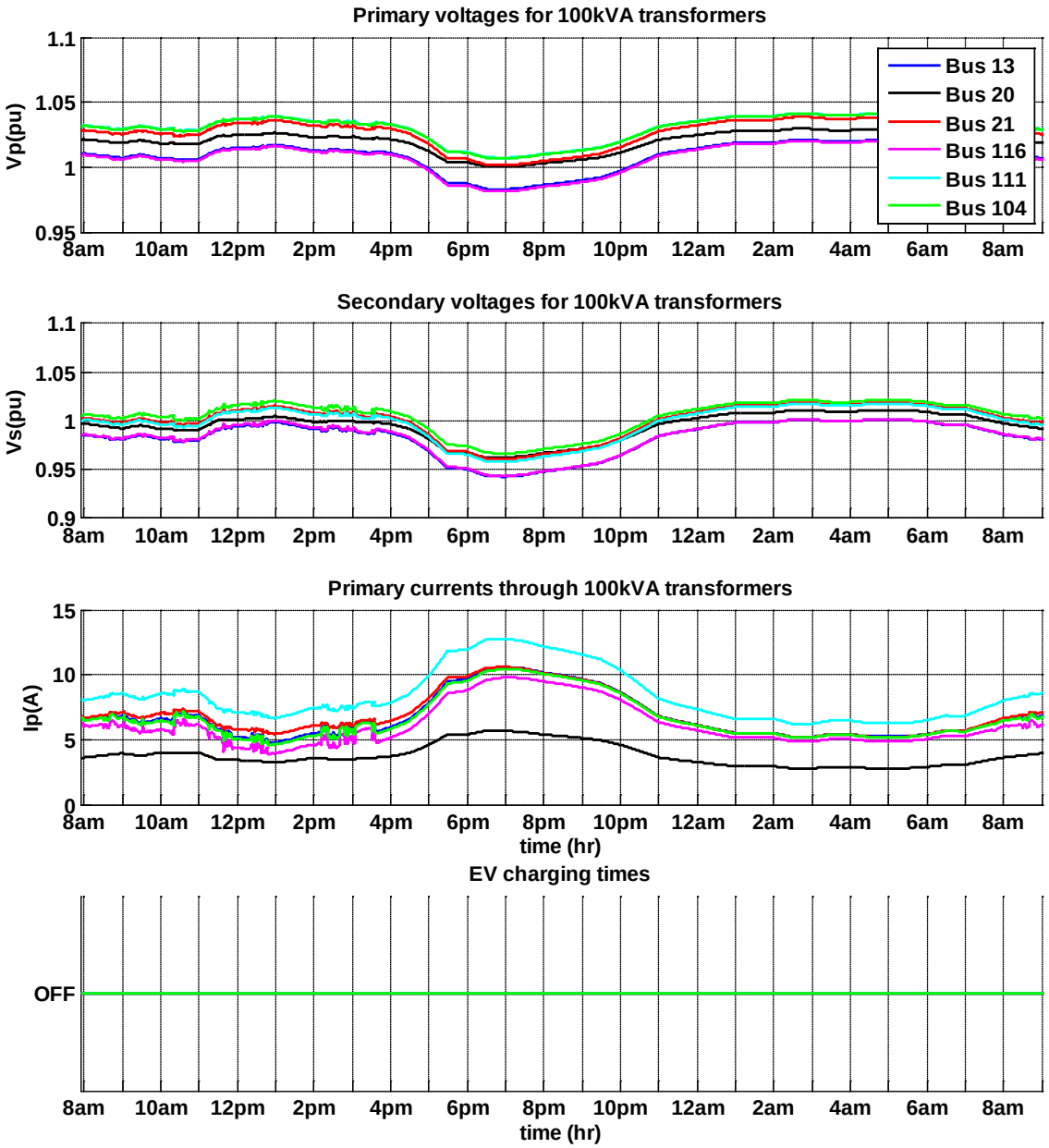

Figure 12 – Primary and secondary voltages and current at 100kVA transformers

3.3 *Offline – Full system test with all existing EV customers*

In this test, EV outputs were added at fourteen (14) existing customer locations. EV sizes and charging times were randomly assigned according to the following sizes and times:

- EV Set 1: random distribution of 3.3kW, 5.8kW, 6.6kW, 9.8kW EV sizes
- Uncontrolled Charging: 16:00 – 18:00 starting times, 22:00 – 4:00 end times
- Controlled Charging: 21:00 – 00:00 starting times, 3:00 – 6:00 end times

The details for EV sizes and charging times for both uncontrolled and controlled charging scenarios are given in ***Table 5***.

Table 5 – EV size and charging times parameters for all existing customers (14)

	Transformer and EV Parameters						
Bus #	Transformer Rated kVA	Connection	Total EV kW	Uncontrolled Charging Start	Uncontrolled Charging End	Controlled Charging Start	Controlled Charging End
13	100	A	3.3	16:30	22:30	23:00	05:00
15	50	AB	3.3	16:00	00:30	21:00	04:30
17	50	AB	5.8	16:30	23:30	23:30	03:00
20	100	AC	6.6	18:00	01:00	21:00	05:00
23	25	B	3.3	17:00	22:30	22:00	03:00
19	50	A	5.8	16:30	23:30	23:30	05:00
116	100	A	6.6	17:30	23:30	21:00	05:30
112	50	B	5.8	17:30	02:30	21:30	05:00
109	50	A	9.8	17:30	22:30	22:30	06:00
106	25	B	9.8	17:00	00:30	23:30	05:00
118A	50	AB	6.6	18:00	01:30	00:00	04:00
118B	50	BC	9.8	16:30	02:00	23:00	05:30
119	50	AB	6.6	17:30	04:00	00:00	03:00
121	25	C	5.8	16:00	02:30	22:00	03:30

3.3.1 Uncontrolled Charging

Voltages for the entire circuit for uncontrolled charging are shown in *Figure 13*. Voltages for selected locations on each subsystem are shown in *Figure 14*. Transformer voltages and currents are shown in *Figure 15*, *Figure 16*, *Figure 17*, *Figure 18*. It should be noted that EV charging indicators are shown for all customers, even though only 14 customers have EV. It is observed that EV charging had a large effect on primary transformer current flow, but only a minor effect on the secondary transformer voltage. EV charging had no significant effect on the circuit voltage for the selected EV penetration

level. As observed, the 25 kVA transformers were mostly affected by the additional loads of the EV chargers, due to low capacity margin to accommodate additional load.

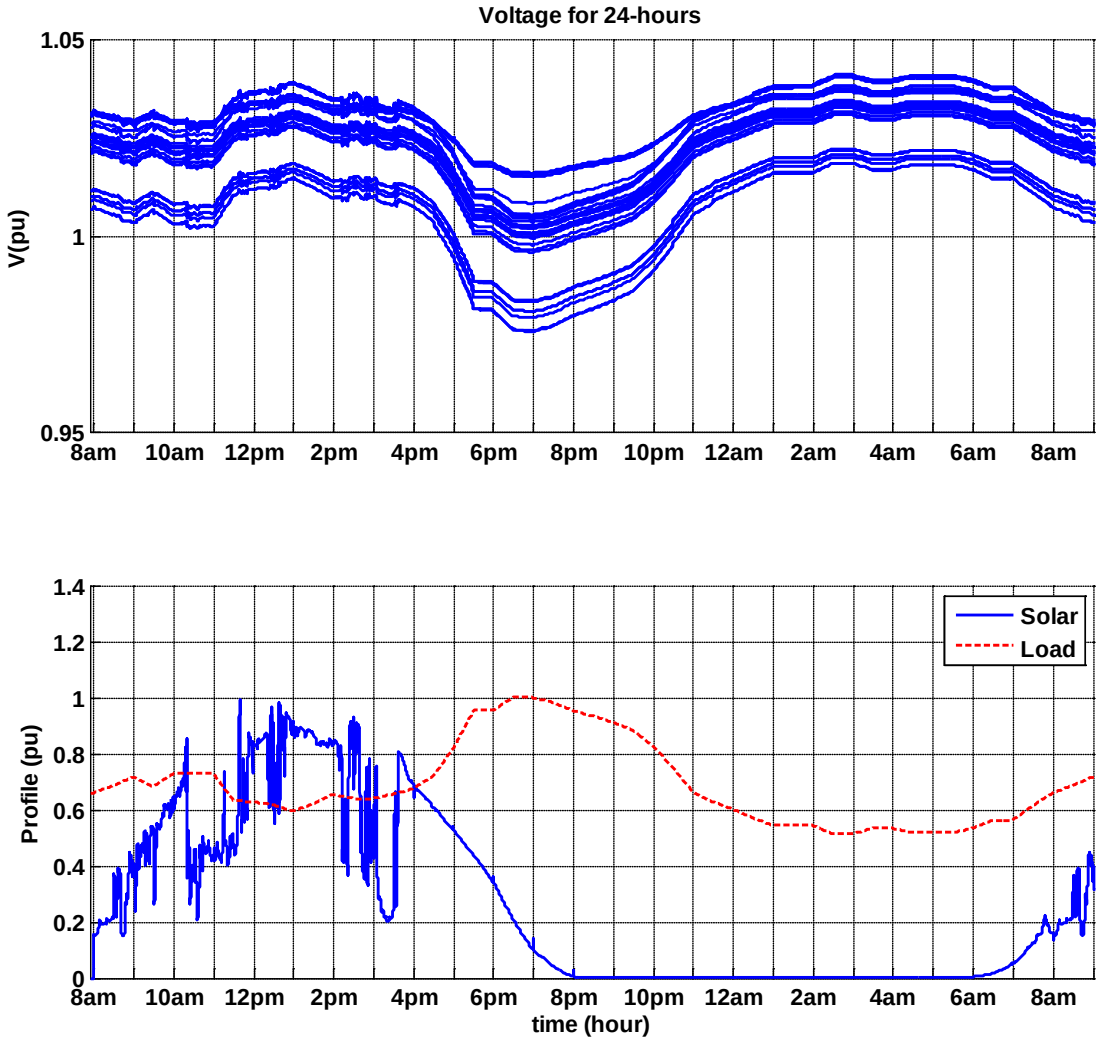

Figure 13 – Voltage at all circuit locations for varying load and PV profile (uncontrolled charging)

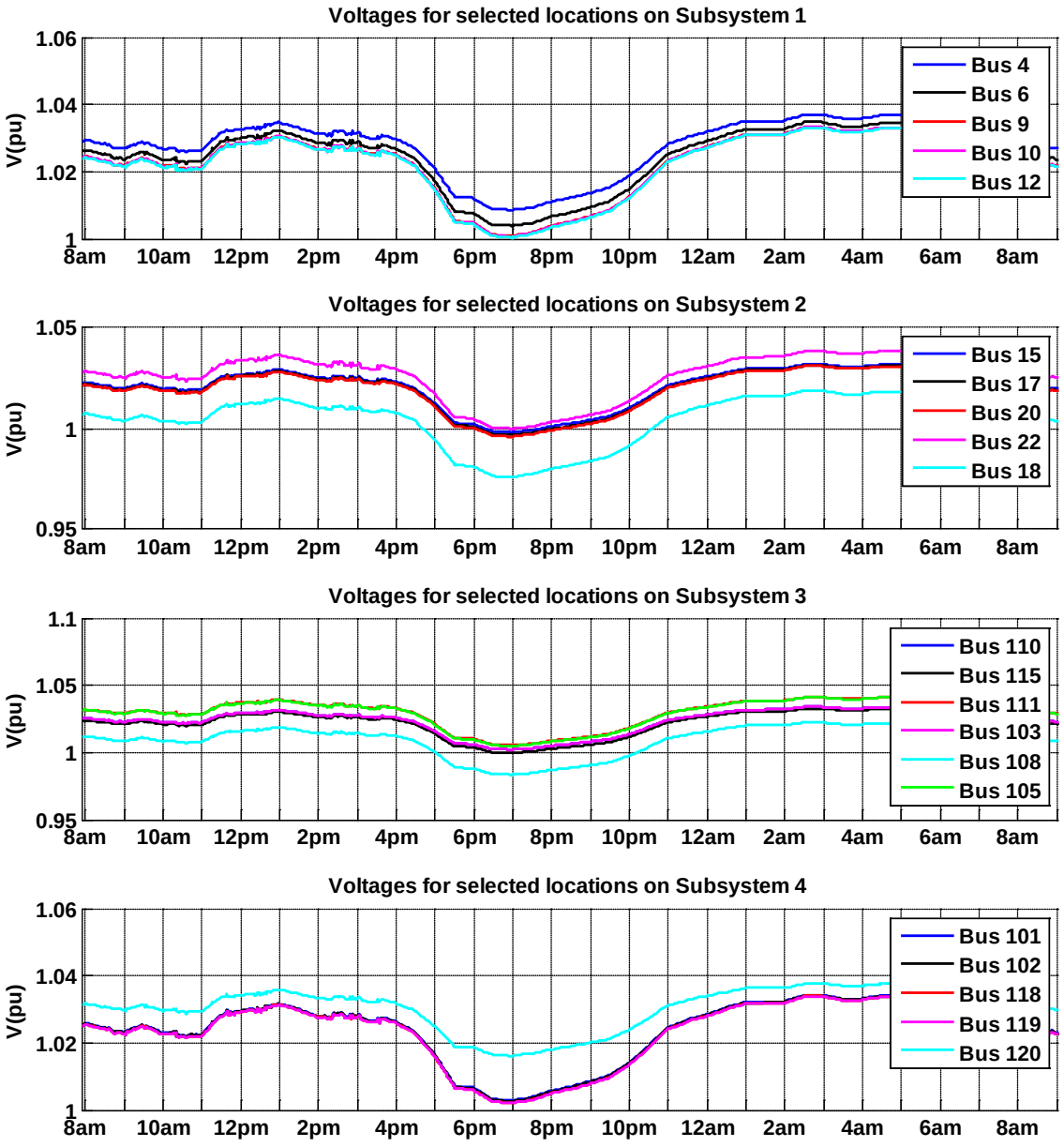

Figure 14 – Voltage at selected circuit locations for varying load and PV profile (uncontrolled charging)

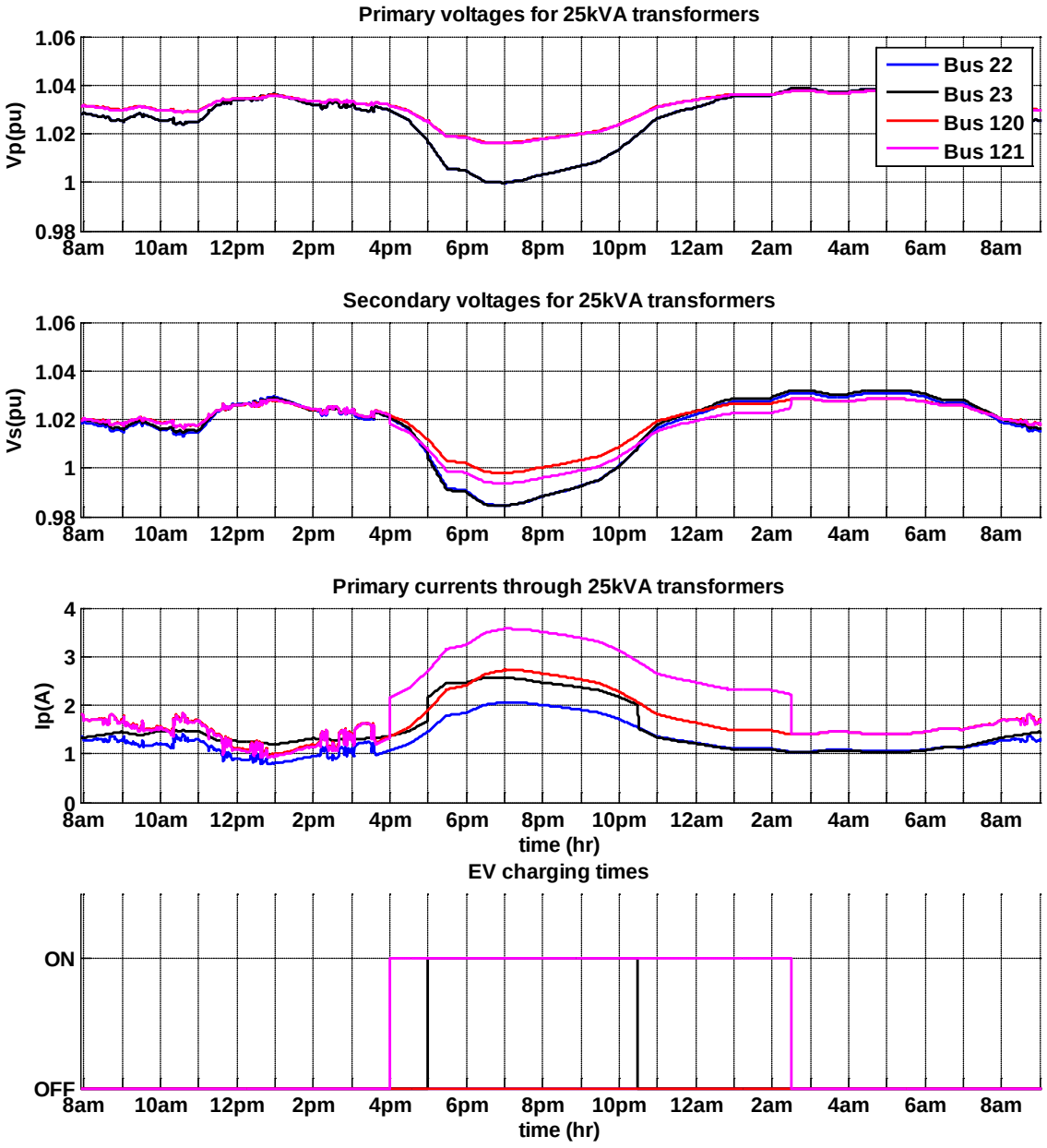

Figure 15 – Primary and secondary voltages and current at 25kVA transformers (uncontrolled charging)

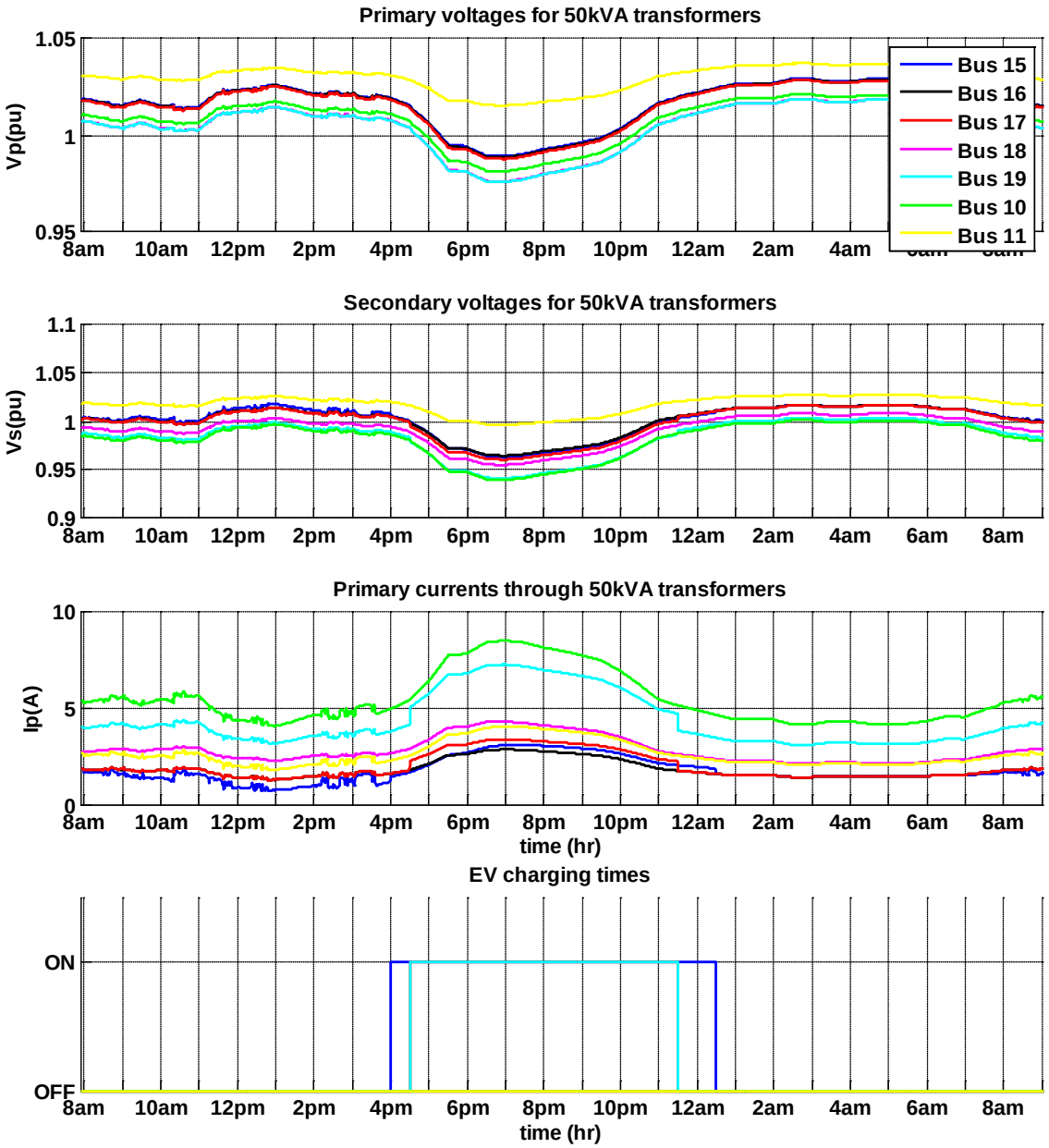

Figure 16 – Primary and secondary voltages and current at 50kVA transformers (uncontrolled charging)

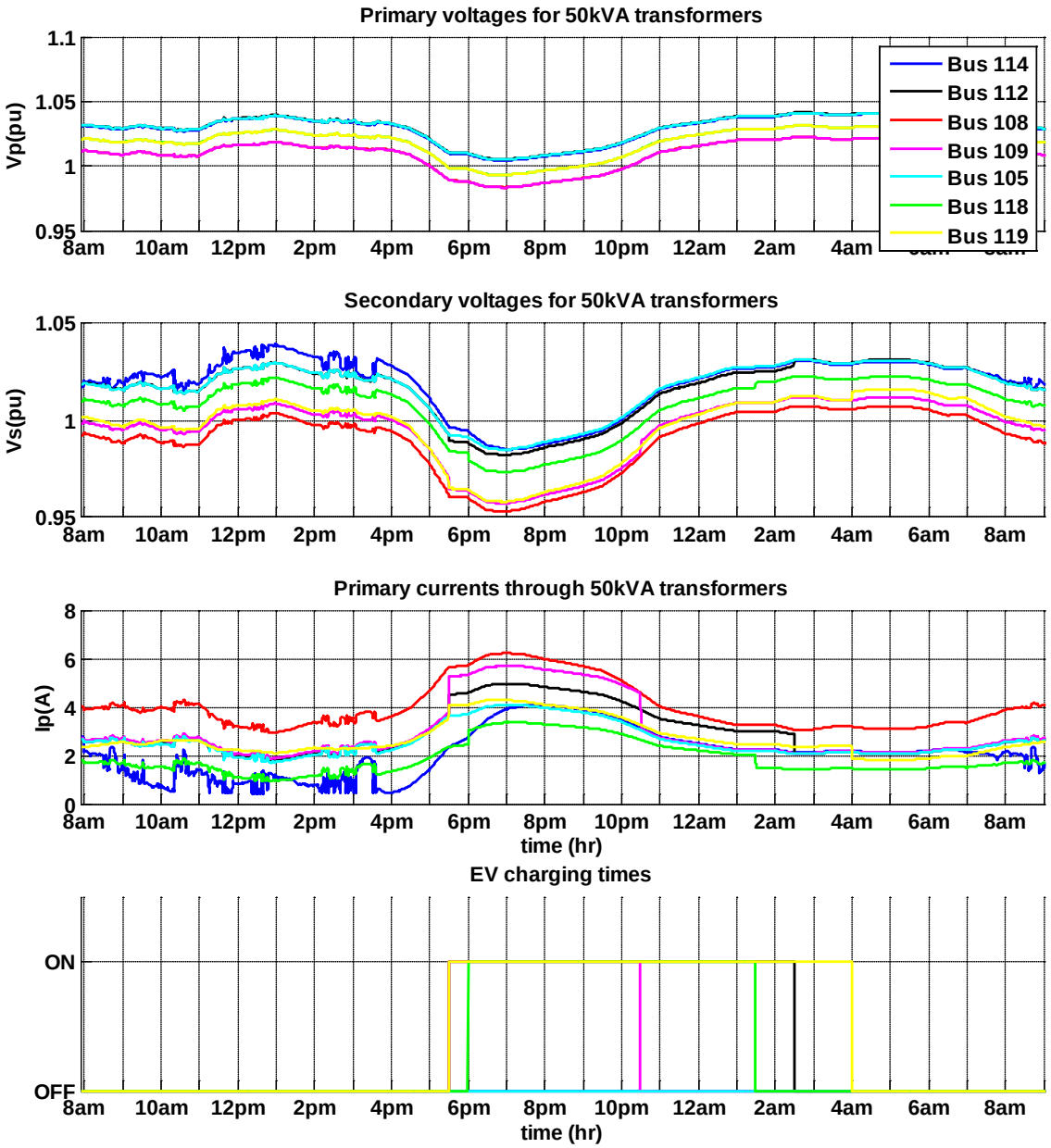

Figure 17 – Primary and secondary voltages and current at 50kVA transformers (uncontrolled charging)

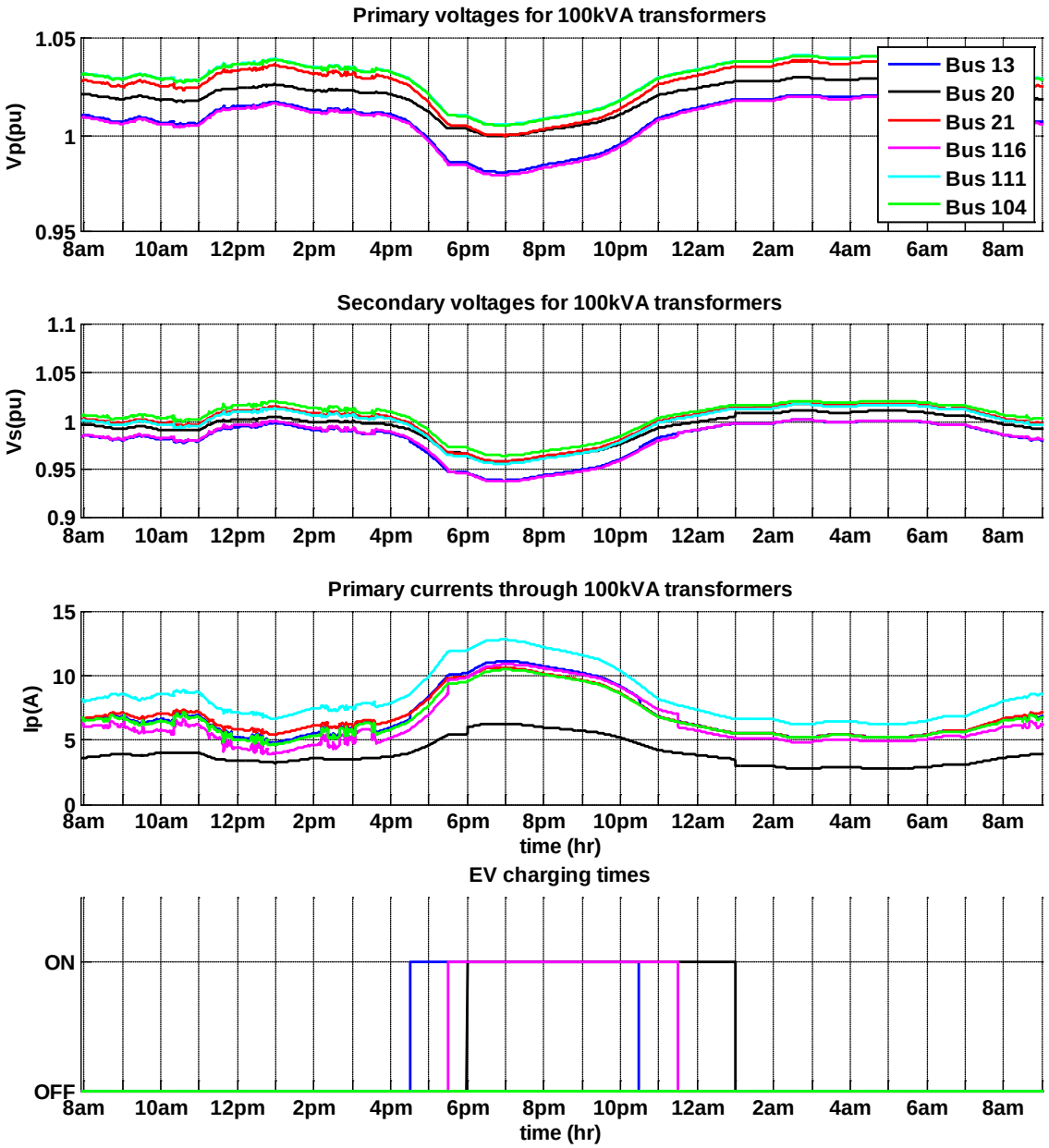

Figure 18 – Primary and secondary voltages and current at 100kVA transformers (uncontrolled charging)

3.3.2 Controlled Charging

Plots for controlled charging are shown in *Figure 19* through *Figure 24*. It was observed that EV charging had a large effect on primary transformer current flow, but only a minor effect on the secondary transformer voltage. However, due to the controlled characteristics of the charging profiles, the increase loading and change in power flow was shifted toward off-peak time of the system. EV charging had no significant effect on the circuit voltage at primary level. The secondary circuits experienced low voltage issues due to further drop in transformer voltages as a result of additional EV charging loads.

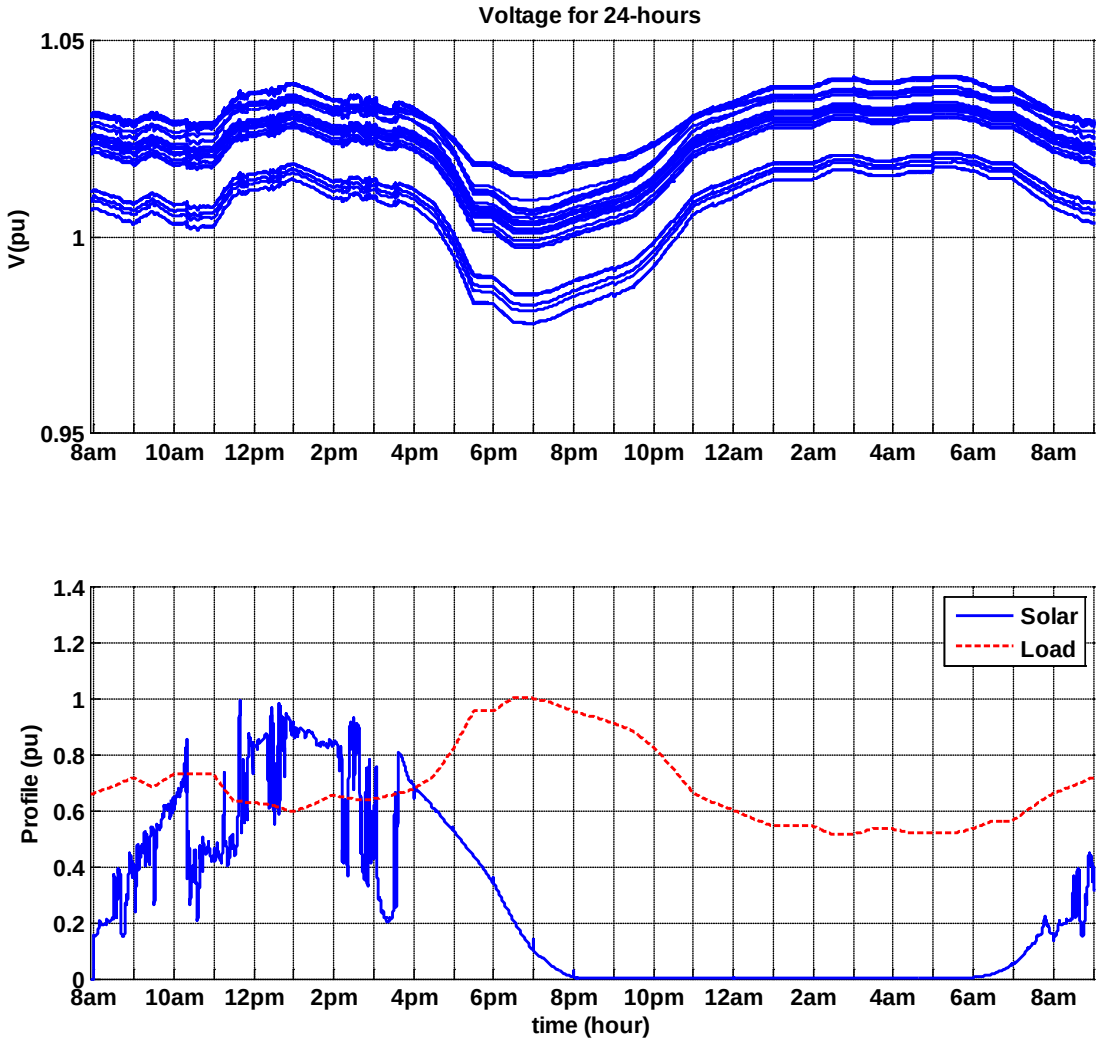

Figure 19 – Voltage at all circuit locations for varying load and PV profile (controlled charging)

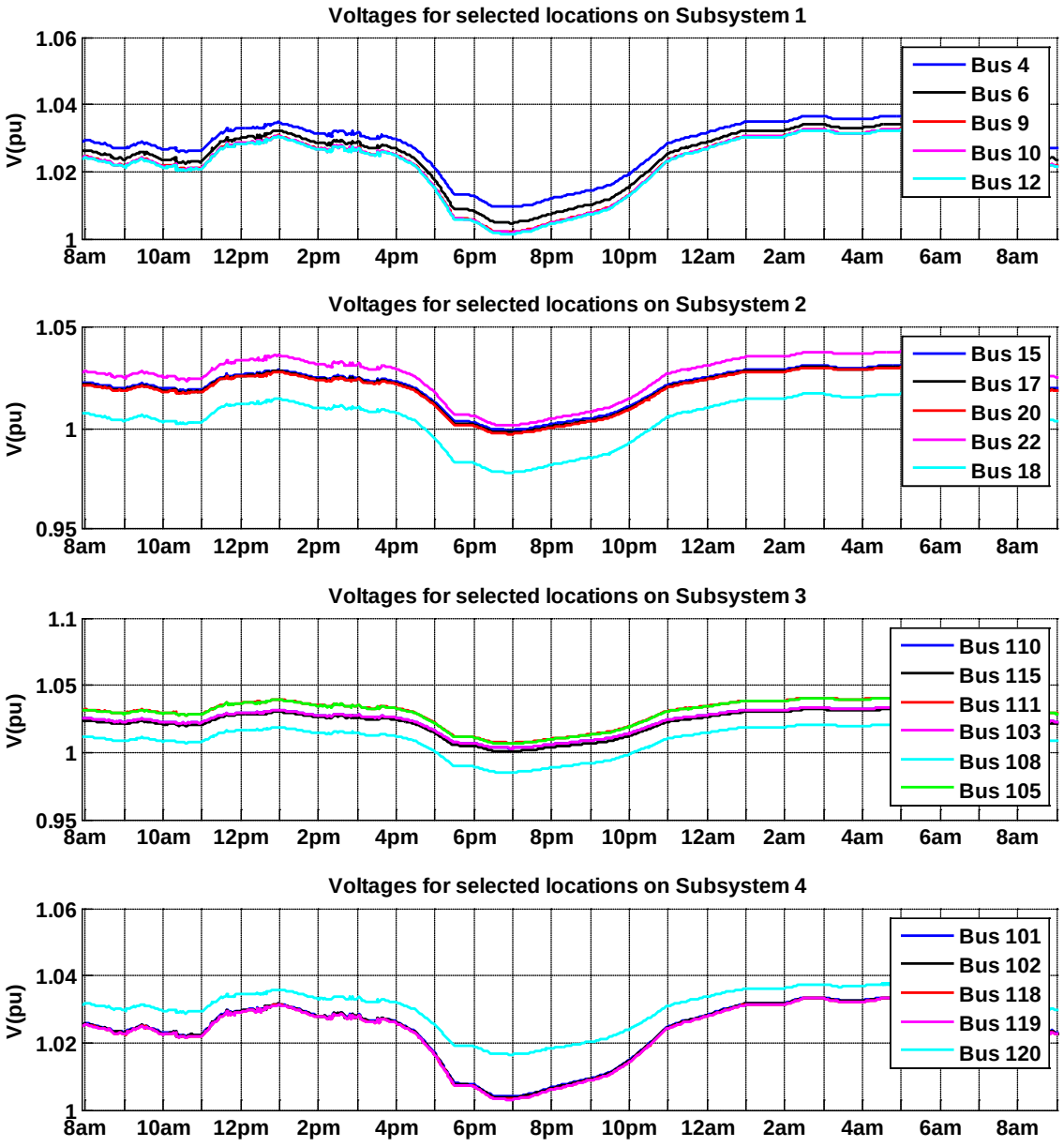

Figure 20 – Voltage at selected circuit locations for varying load and PV profile (controlled charging)

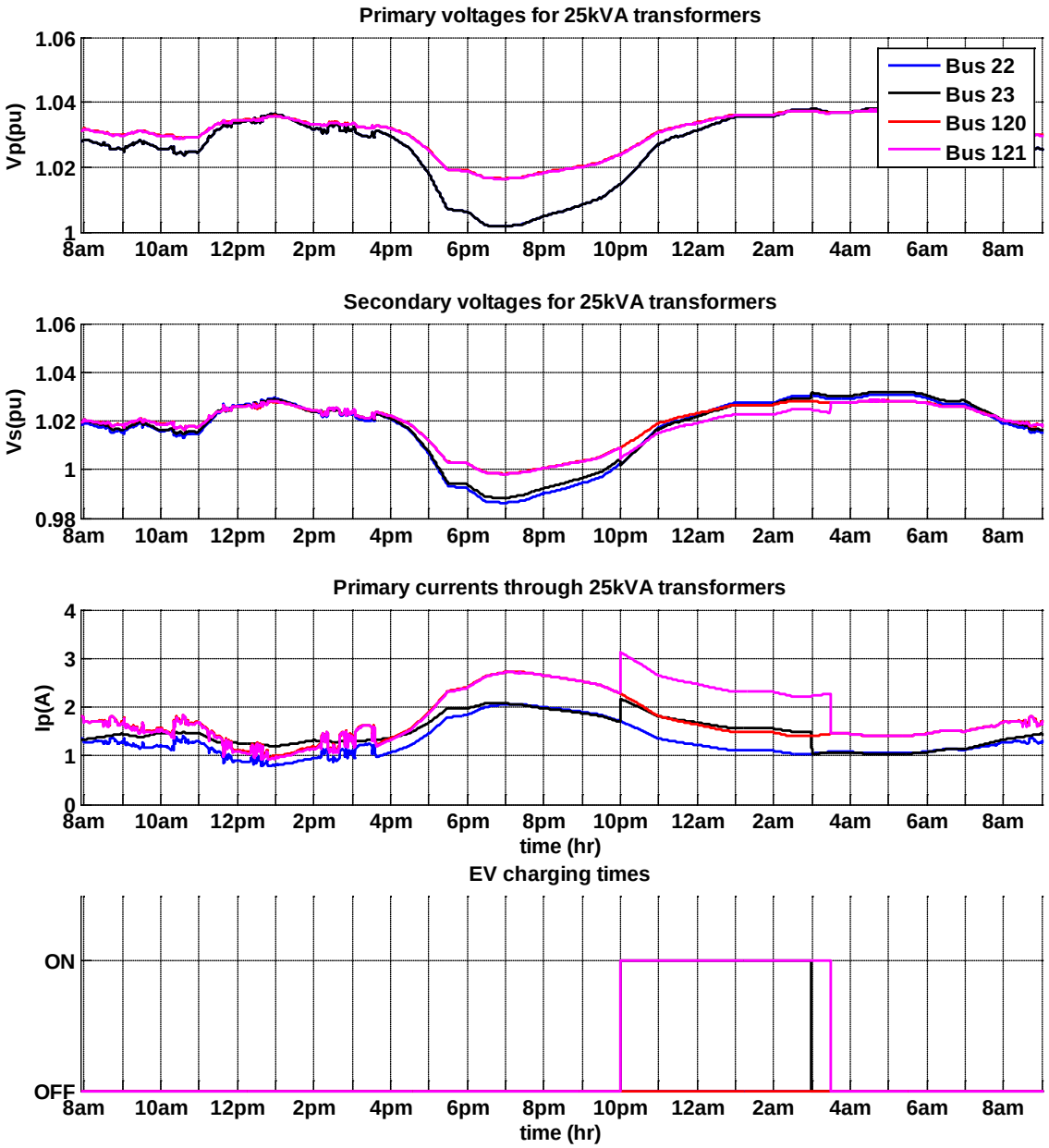

Figure 21 – Primary and secondary voltages and current at 25kVA transformers (controlled charging)

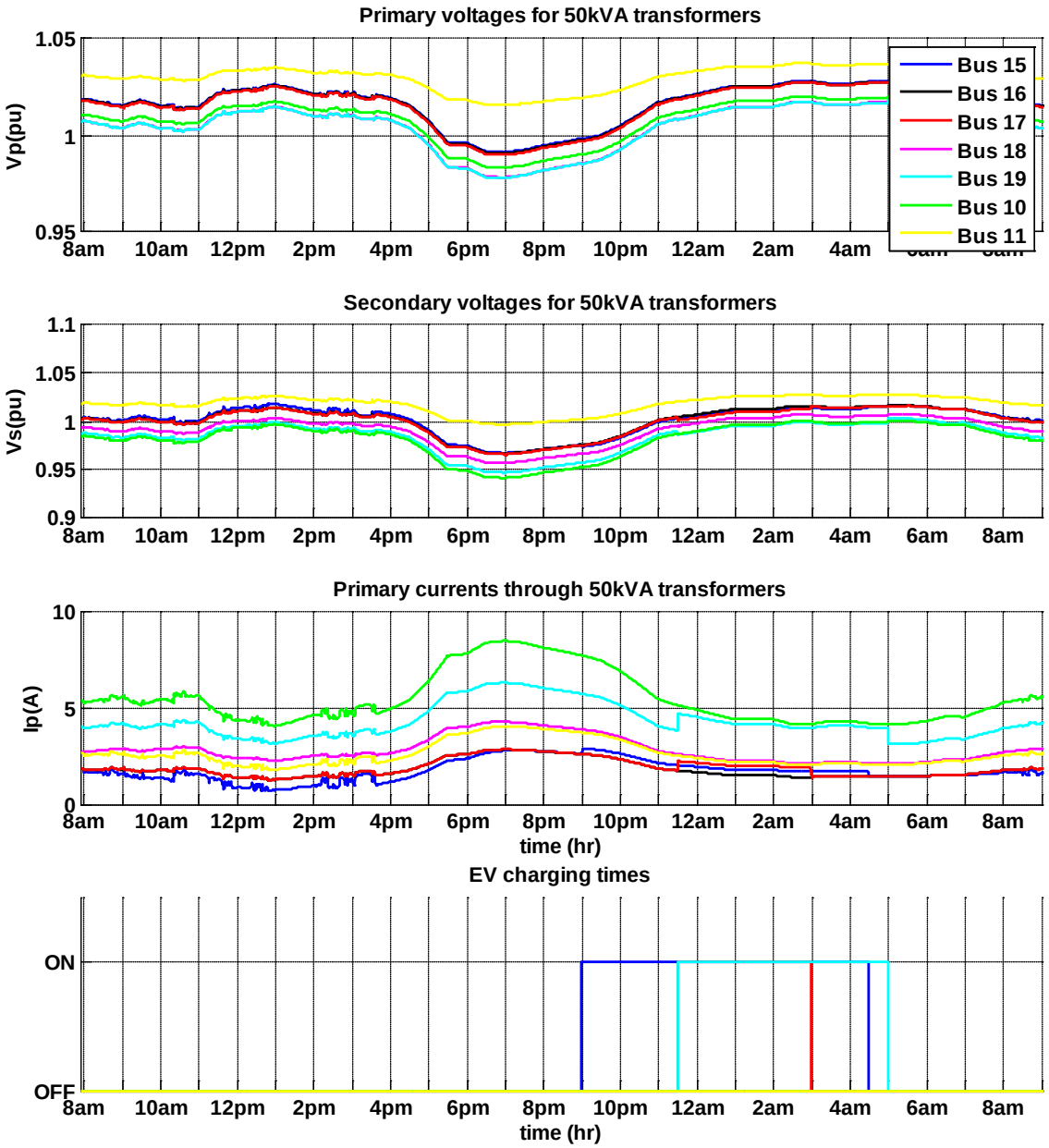

Figure 22 – Primary and secondary voltages and current at 50kVA transformers (controlled charging)

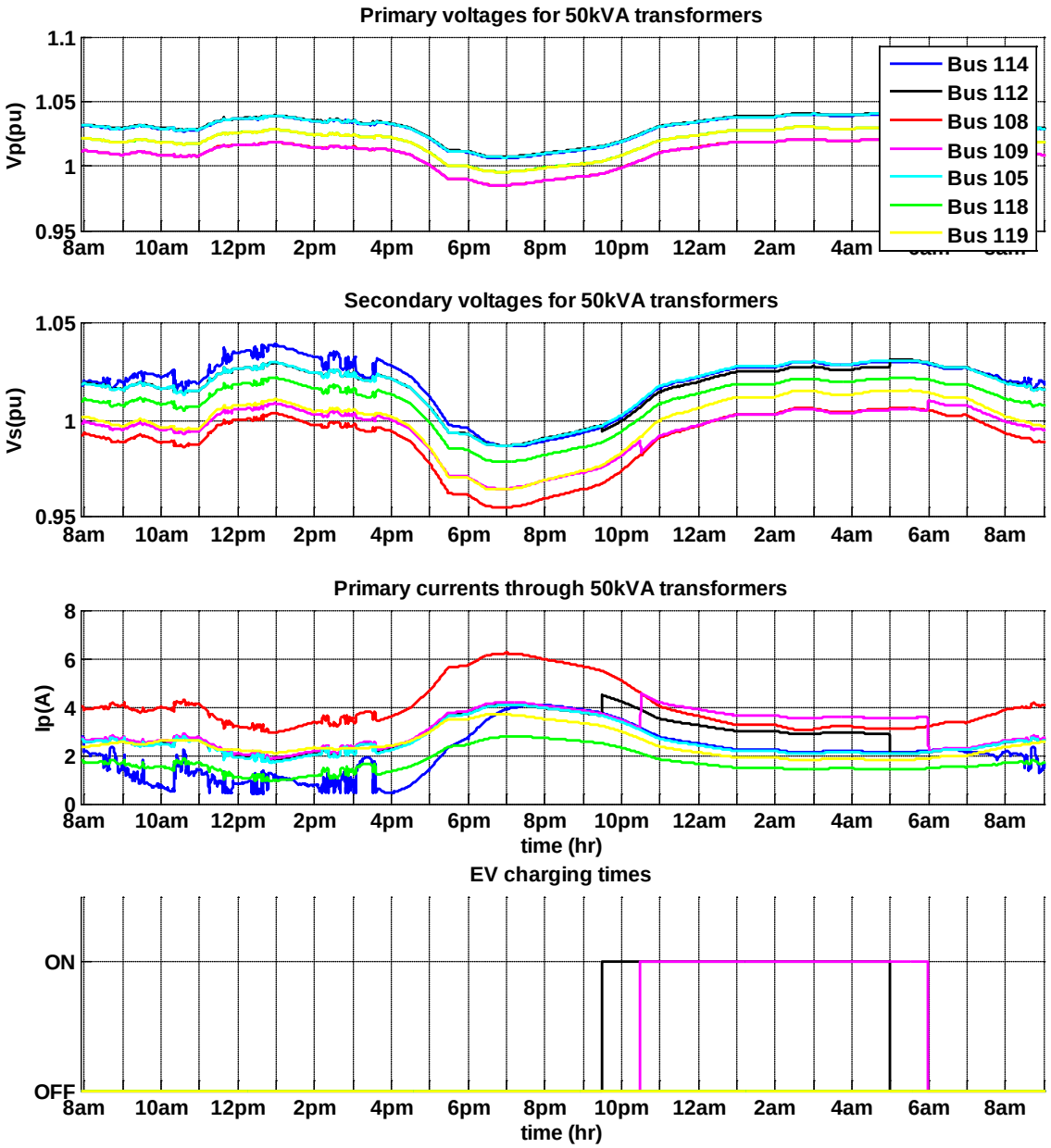

Figure 23 – Primary and secondary voltages and current at 50kVA transformers (controlled charging)

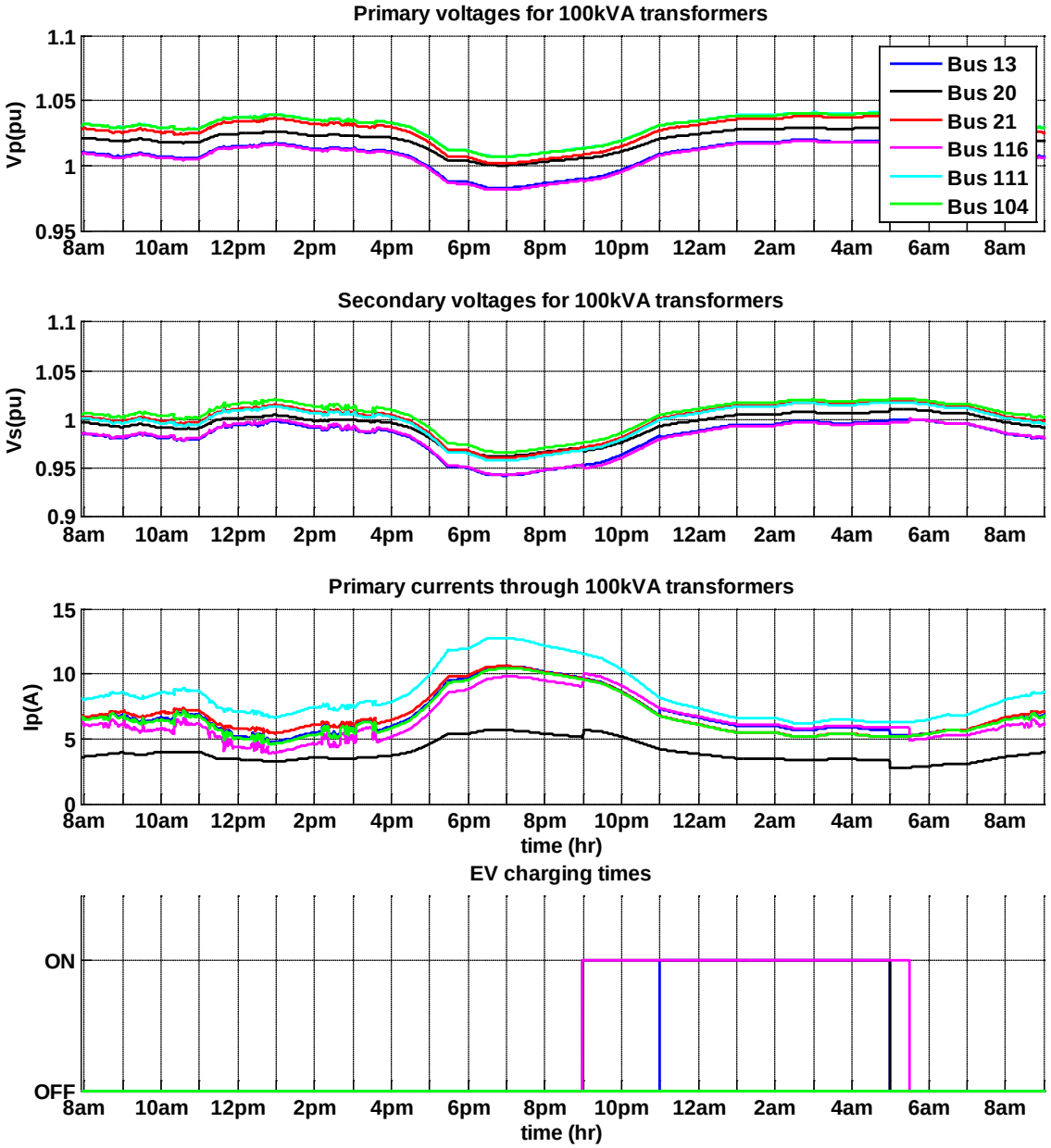

Figure 24 – Primary and secondary voltages and current at 100kVA transformers (controlled charging)

3.4 *Offline – Full system test with EV for all customers*

In this test, EV outputs were added to all customer locations (transformer secondary circuits). EV sizes and charging times were randomly assigned according the following sizes and times:

- EV Set 1: Random distribution of 3.3kW, 5.8kW, 6.6kW, 9.8kW EV sizes
- Uncontrolled Charging: 16:00 – 18:00 starting times, 22:00 – 4:00 end times
- Controlled Charging: 21:00 – 00:00 starting times, 3:00 – 6:00 end times

The details for EV size and charging times for both uncontrolled and controlled charging scenarios are given in ***Table 6***, with the original 14 EV customers being shaded.

Table 6 – EV size and charging times parameters for all customers

	Transformer and EV Parameters						
Bus #	Transformer Rated kVA	Connection	Total EV kW	Uncontrolled Charging Start	Uncontrolled Charging End	Controlled Charging Start	Controlled Charging End
10	50	A	9.8	17:00	01:30	21:30	04:00
11	50	C	6.6	17:00	00:30	23:30	03:00
13	100	A	3.3	16:30	22:30	23:00	05:00
15	50	AB	3.3	16:00	00:30	21:00	04:30
16	50	AB	5.8	17:00	01:00	00:00	03:00
17	50	AB	5.8	16:30	23:30	23:30	03:00
20	100	AC	6.6	18:00	01:00	21:00	05:00
21	100	B	5.8	16:30	03:00	23:00	05:00
22	25	B	9.8	16:30	03:00	21:30	06:00
23	25	B	3.3	17:00	22:30	22:00	03:00
18	50	A	3.3	16:00	22:00	22:00	03:30
19	50	A	5.8	16:30	23:30	23:30	05:00
113	50	C	6.6	16:00	02:00	00:00	04:30
114	50	B	5.8	16:30	01:30	23:30	05:00
116	100	A	6.6	17:30	23:30	21:00	05:30
111	100	B	5.8	16:00	23:00	22:00	03:00
112	50	B	5.8	17:30	02:30	21:30	05:00
107	50	A	5.8	17:30	00:00	00:00	04:00
108	50	A	6.6	18:00	03:00	21:00	05:00
109	50	A	9.8	17:30	22:30	22:30	06:00
104	100	B	9.8	17:00	02:30	21:00	03:30
105	50	B	5.8	18:00	23:30	23:30	05:30
106	25	B	9.8	17:00	00:30	23:30	05:00
118A	50	AB	6.6	18:00	01:30	00:00	04:00
118B	50	BC	9.8	16:30	02:00	23:00	05:30
119	50	AB	6.6	17:30	04:00	00:00	03:00
120	25	C	9.8	17:30	00:30	00:00	05:30
121	25	C	5.8	16:00	02:30	22:00	03:30

3.4.1 Uncontrolled Charging

Voltages for the entire circuit for uncontrolled charging are shown in *Figure 25*. Voltages for selected locations on each subsystem are shown in *Figure 26*. Transformer voltages and currents are shown in *Figure 27*, *Figure 28*, *Figure 29*, and *Figure 30*. It was observed that EV charging had a large effect on primary transformer current flow (20% to 30% increase in loading). The effect on the secondary transformer voltages were in the 1-2% range. EV charging had a minor effect on the primary circuit voltages at 12 kV. The transformer size should match the expected EV charging loads.

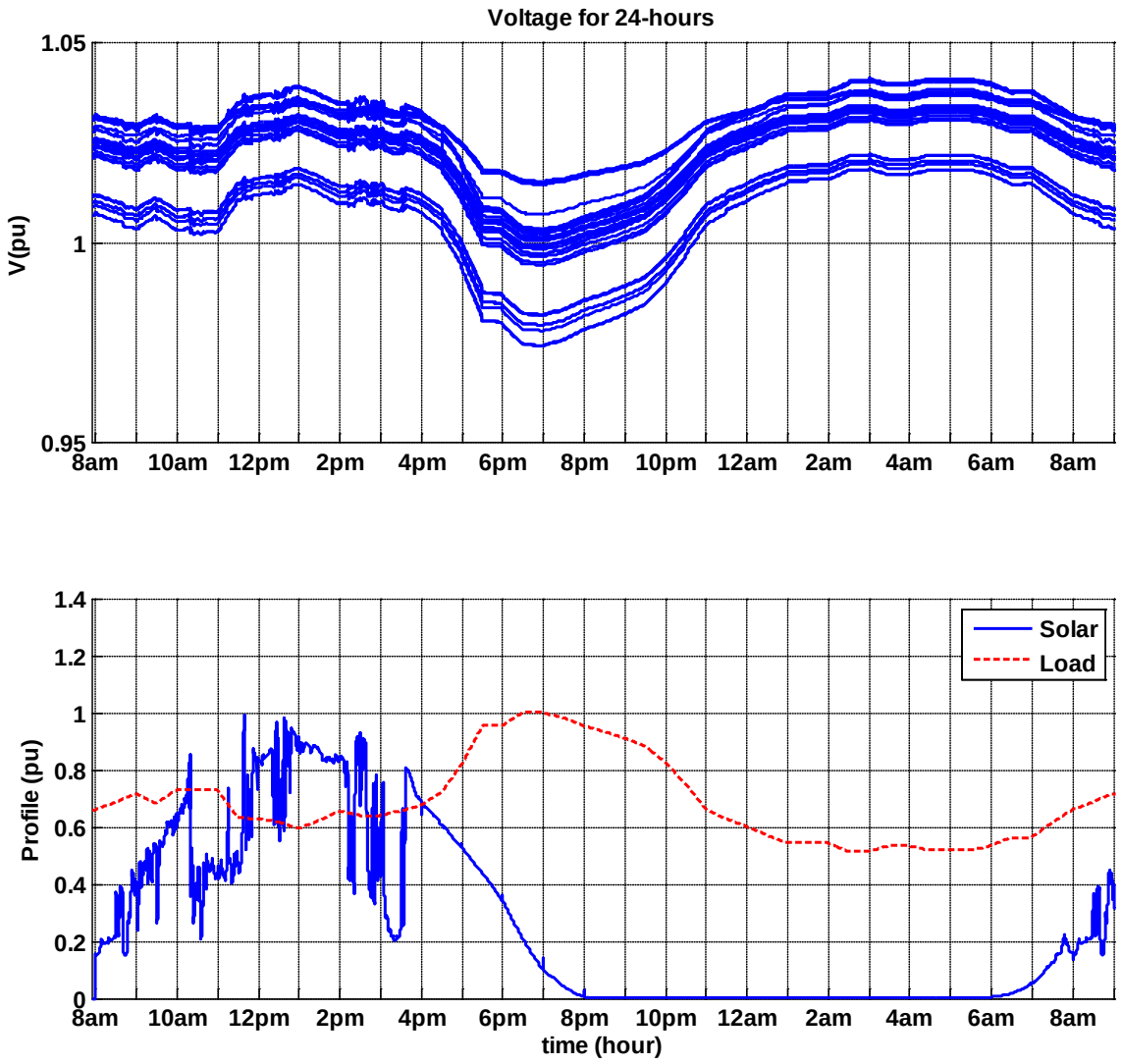

Figure 25 – Voltage at all circuit locations for varying load and PV profile (uncontrolled charging)

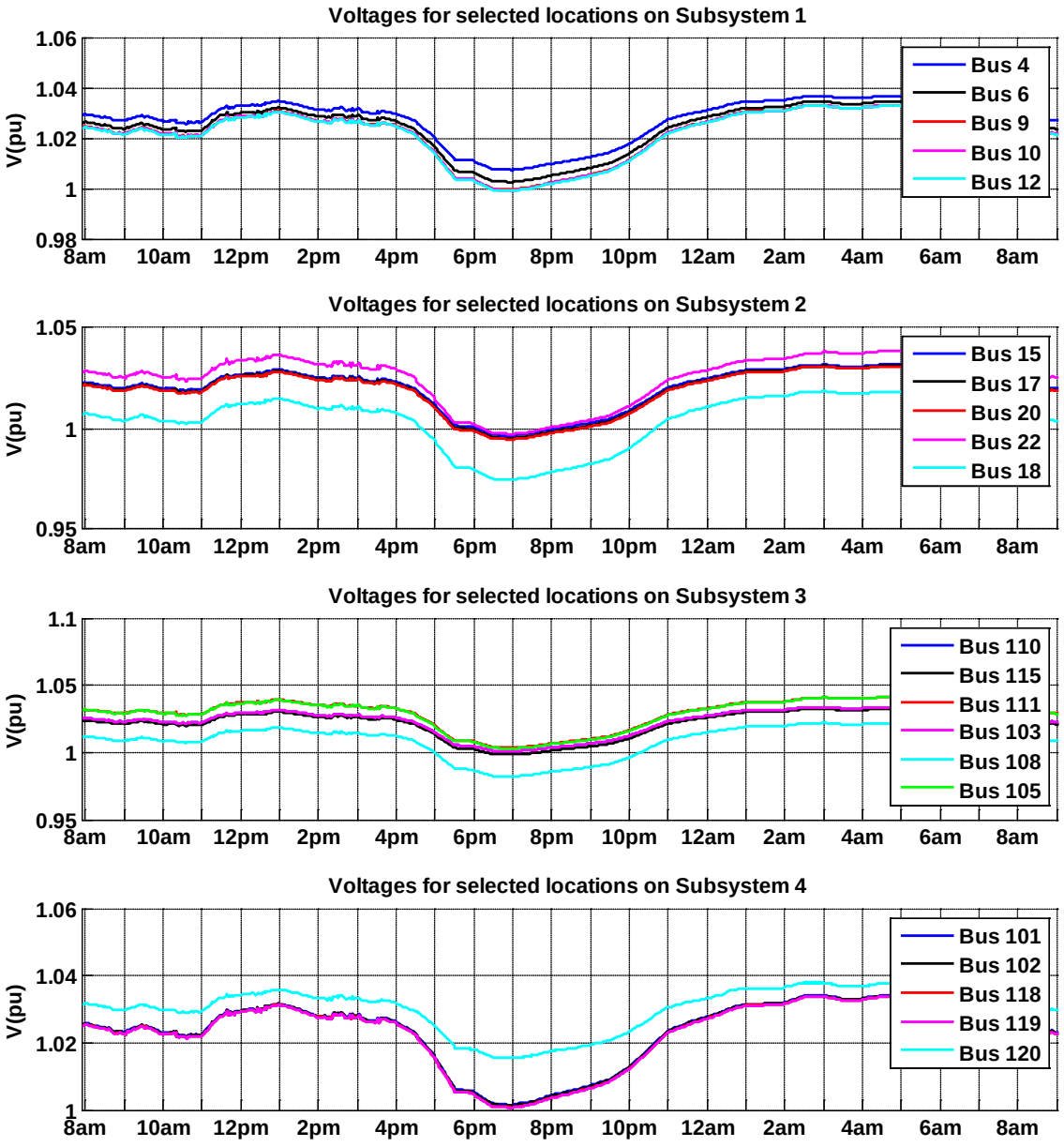

Figure 26 – Voltage at selected circuit locations for varying load and PV profile (uncontrolled charging)

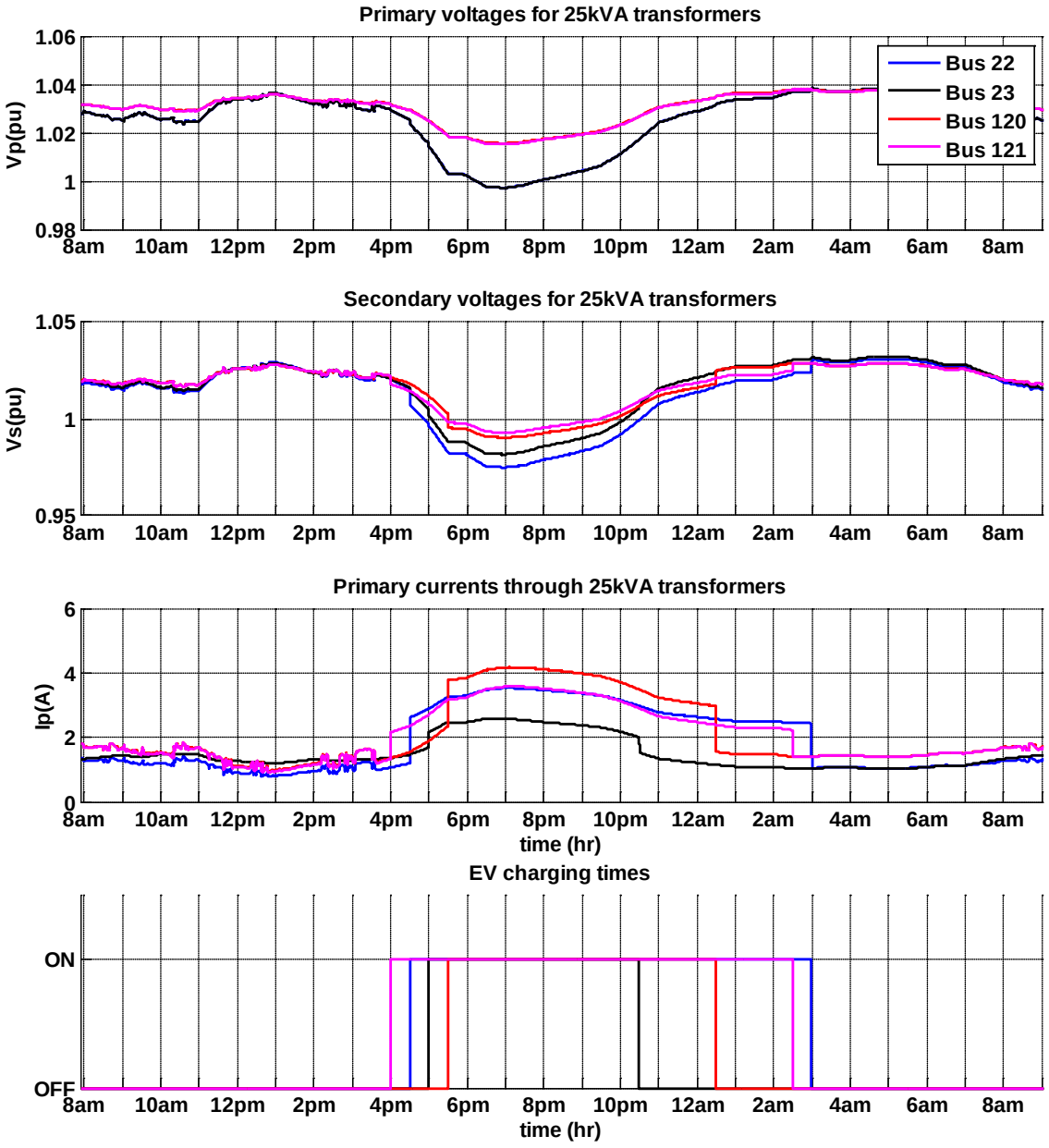

Figure 27 – Primary and secondary voltages and current at 25kVA transformers (uncontrolled charging)

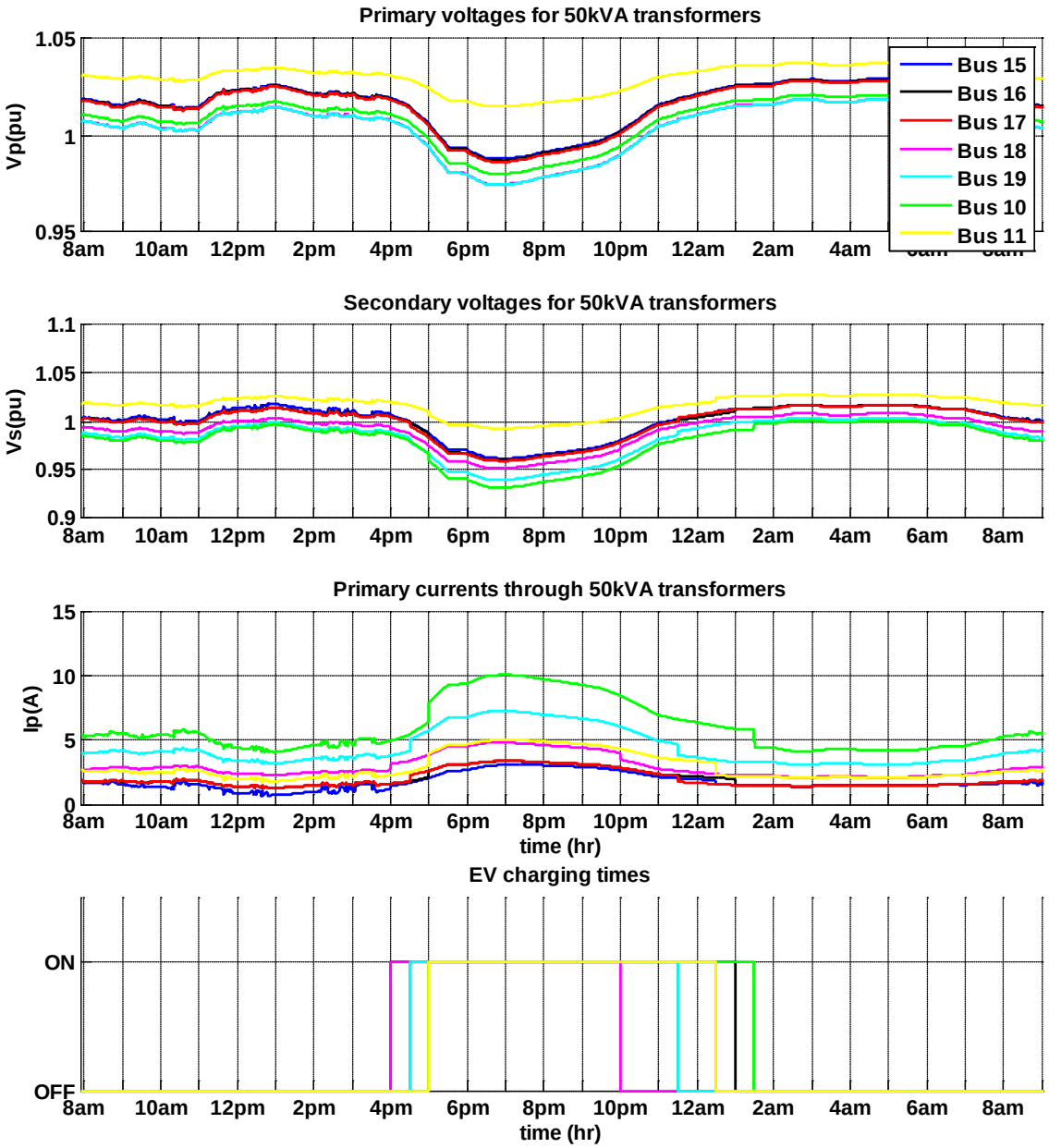

Figure 28 – Primary and secondary voltages and current at 50kVA transformers (uncontrolled charging)

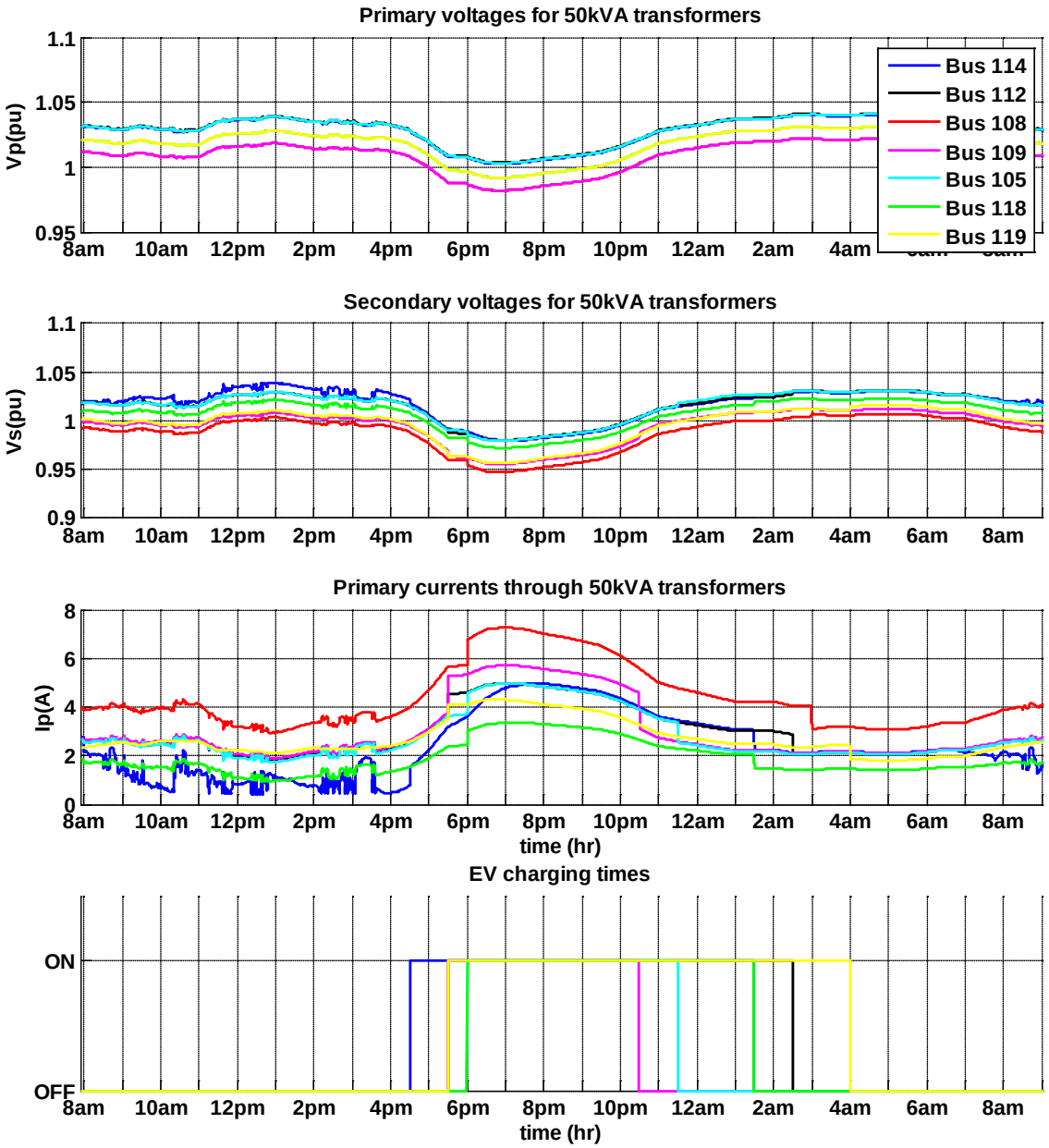

Figure 29 – Primary and secondary voltages and current at 50kVA transformers (uncontrolled charging)

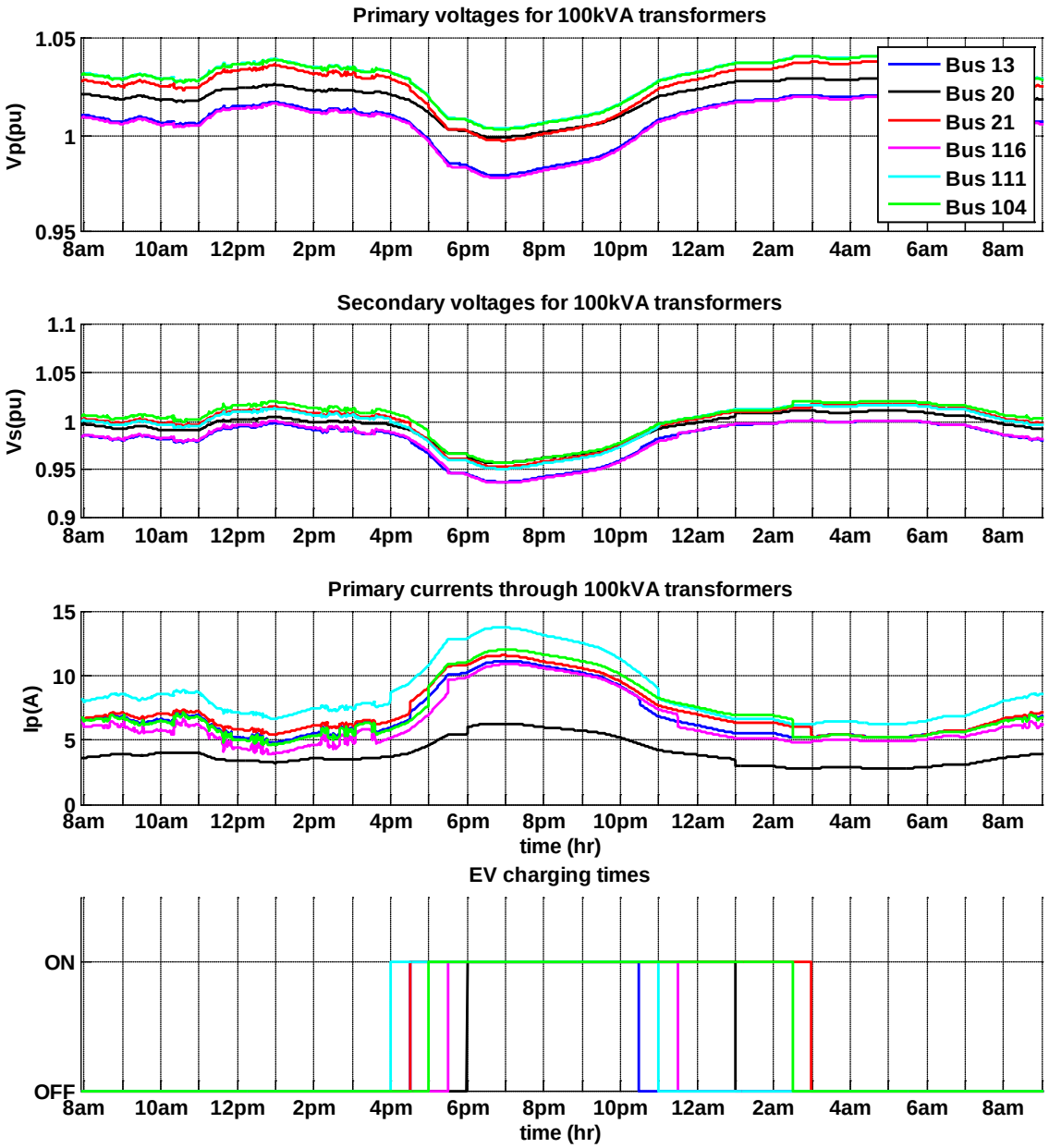

Figure 30 – Primary and secondary voltages and current at 100kVA transformers (uncontrolled charging)

3.4.1 Controlled Charging

Plots for controlled charging are shown in *Figure 31* through *Figure 36*. It was observed that EV charging had a large effect on primary transformer current flow, but only a minor effect on the primary transformer voltages at this penetration level. In addition, because the controlled charging mostly occurred during late evening time, voltage was higher at that time compare to the late afternoon or early evening. Hence, the impact on the secondary voltage drop was lower comparing to the un-controlled scenarios.

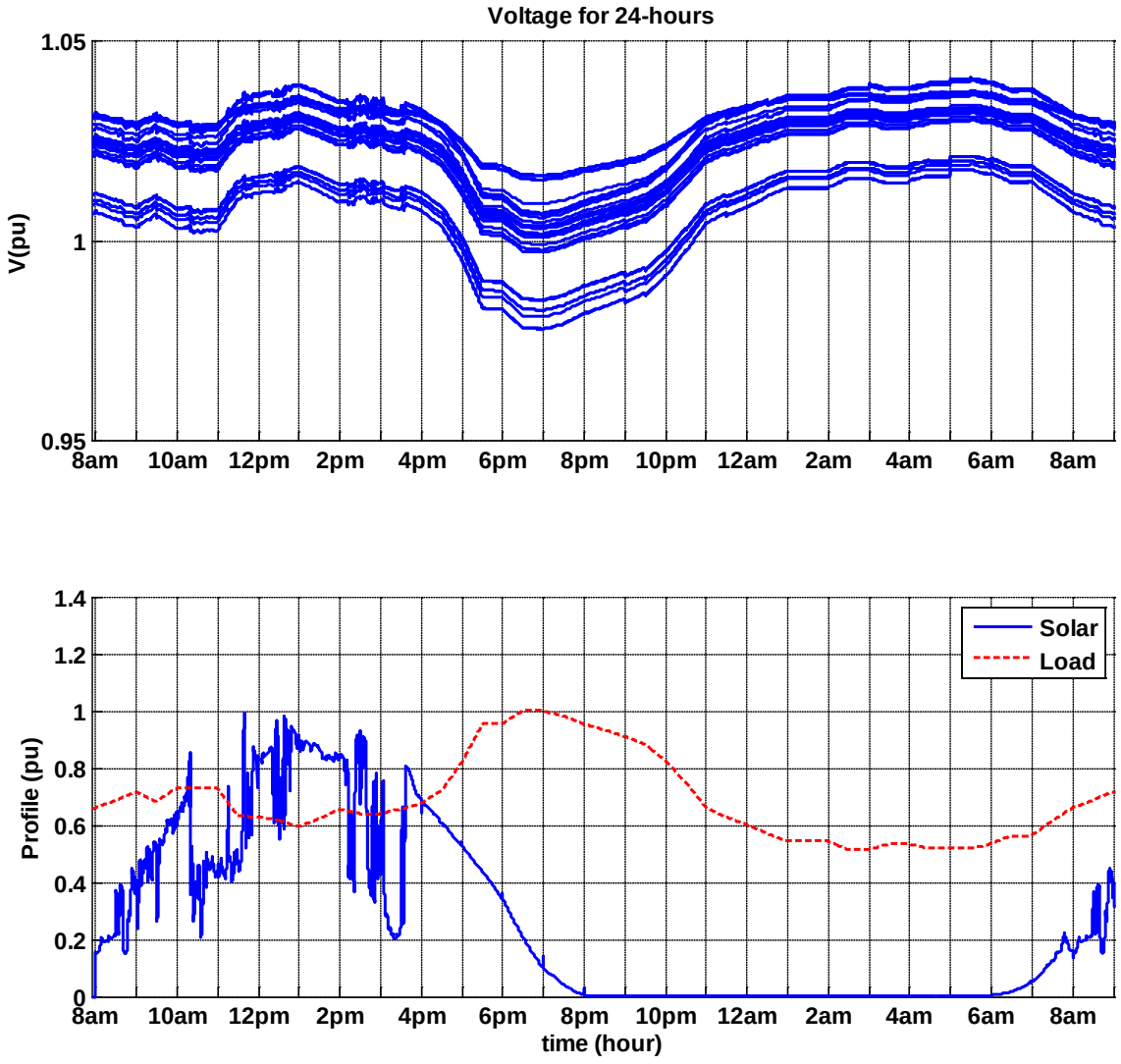

Figure 31 – Voltage at all circuit locations for varying load and PV profile (controlled charging)

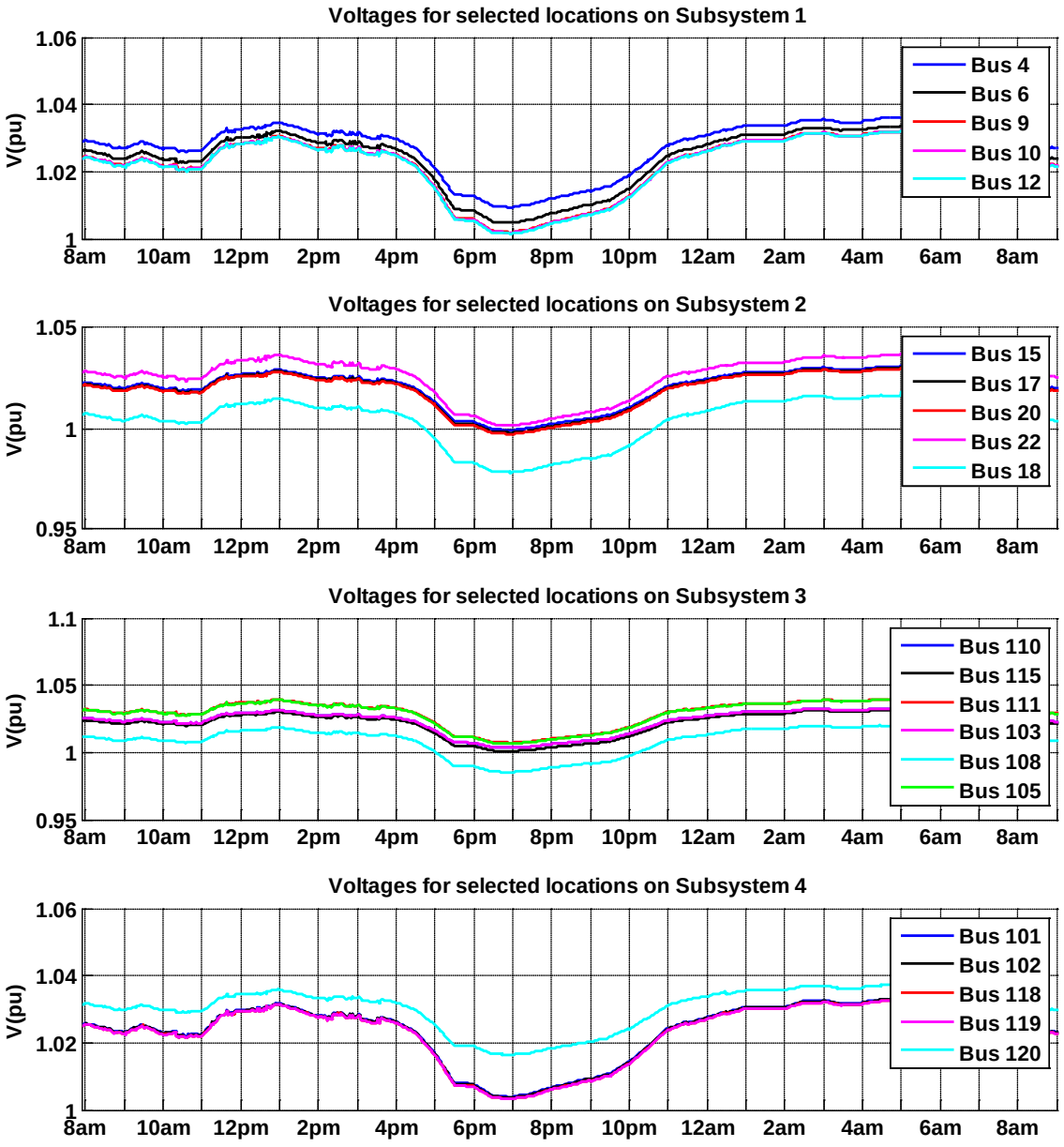

Figure 32 – Voltage at selected circuit locations for varying load and PV profile (controlled charging)

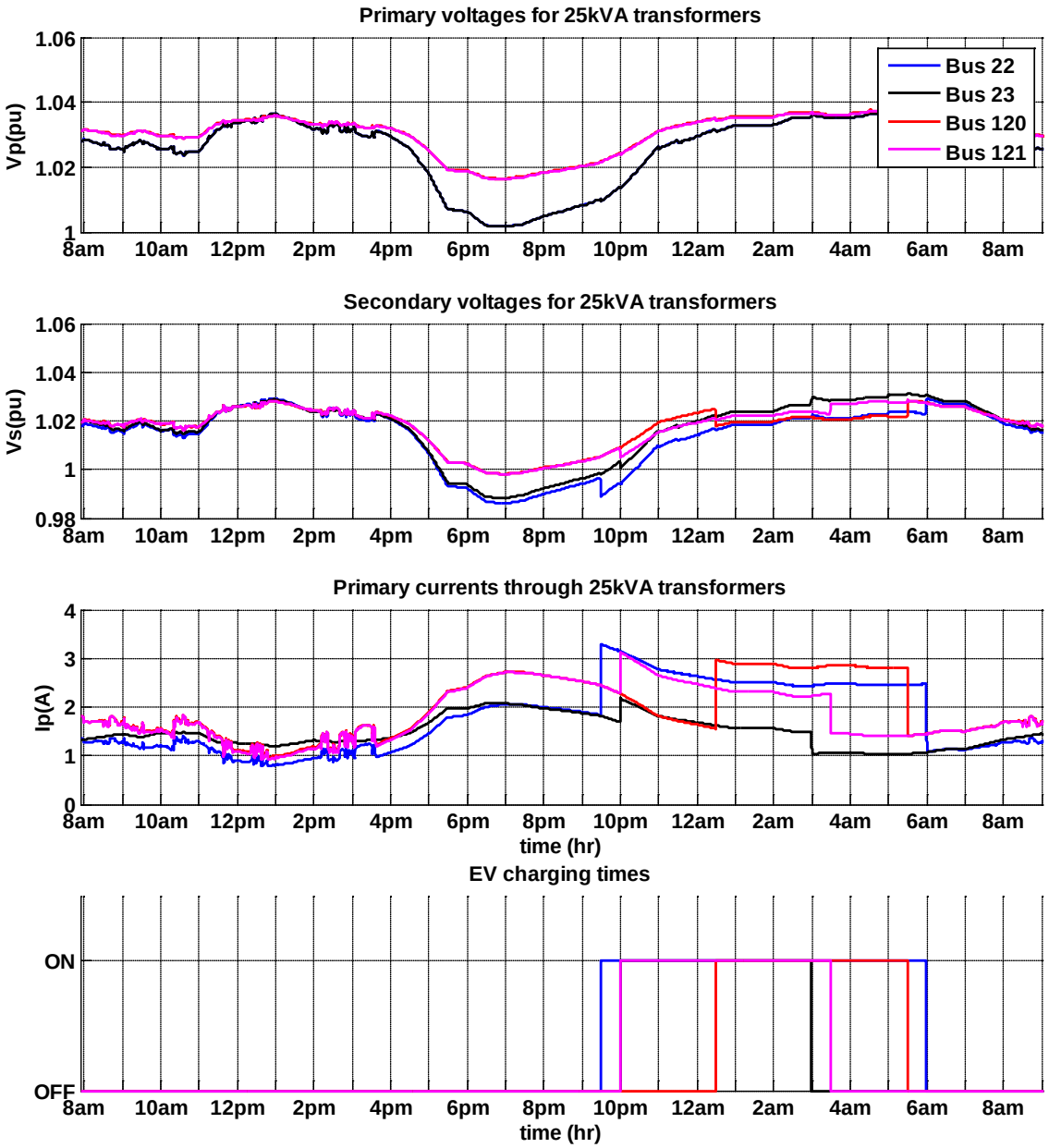

Figure 33 – Primary and secondary voltages and current at 25kVA transformers (controlled charging)

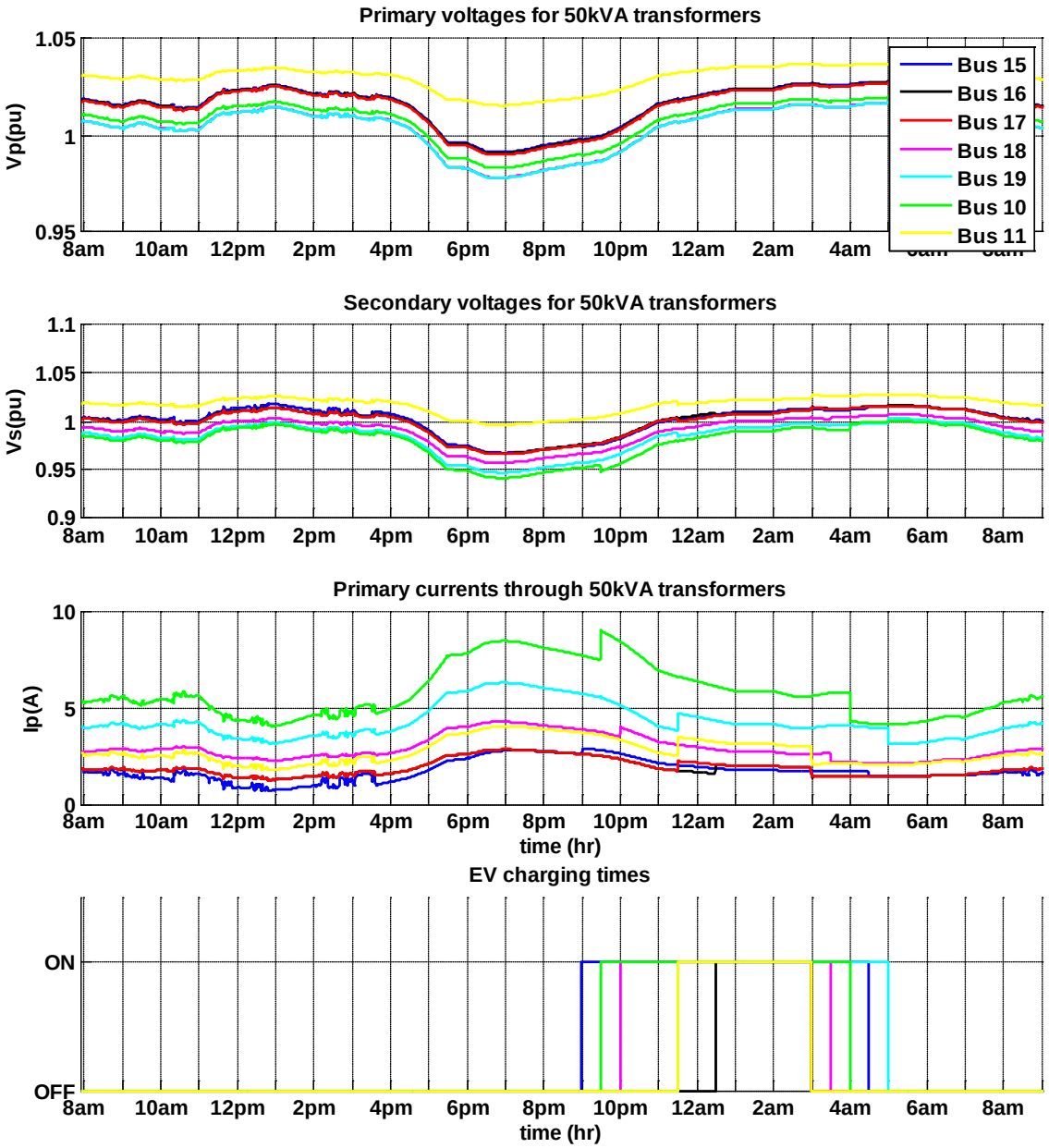

Figure 34 – Primary and secondary voltages and current at 50kVA transformers (controlled charging)

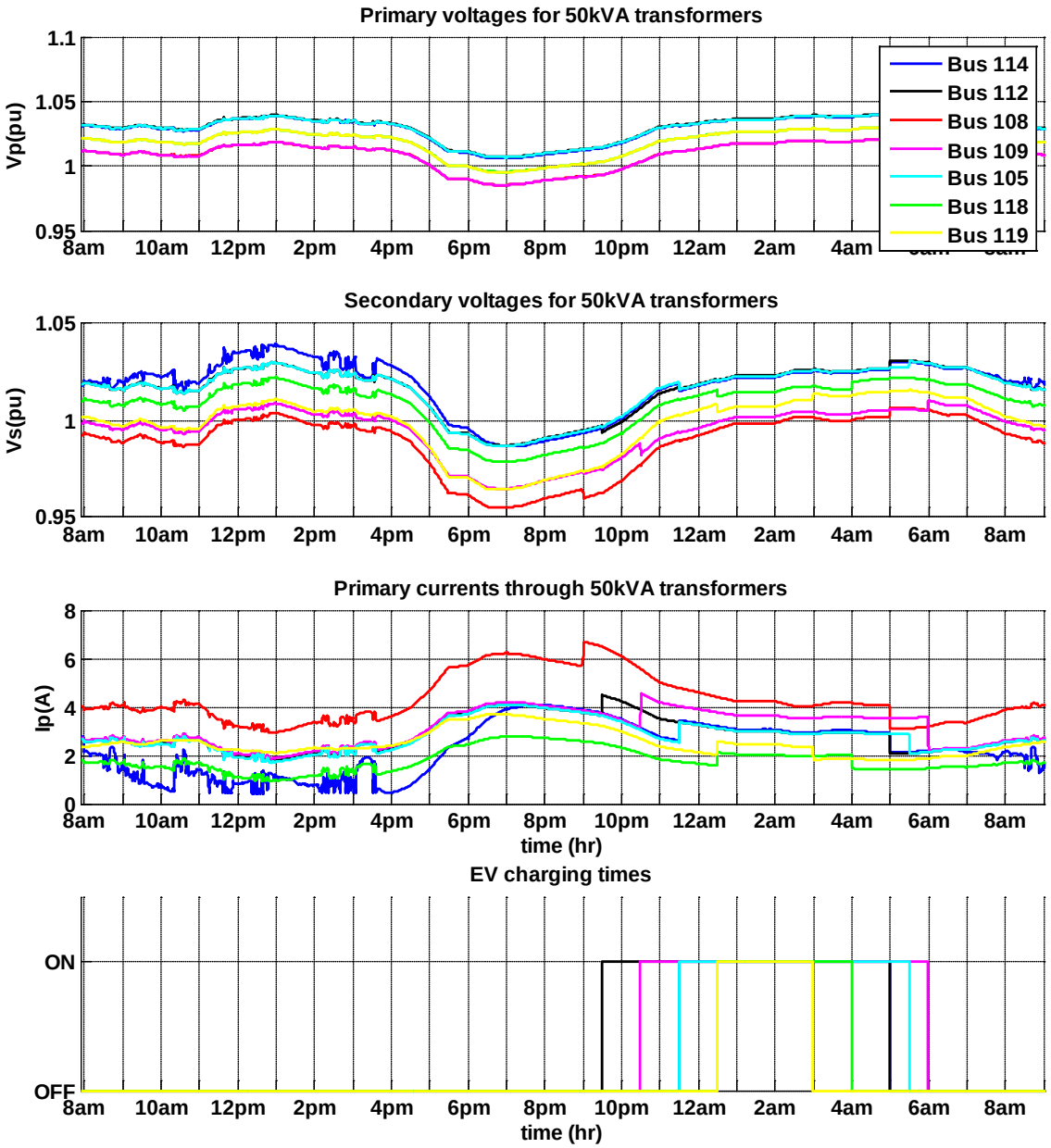

Figure 35 – Primary and secondary voltages and current at 50kVA transformers (controlled charging)

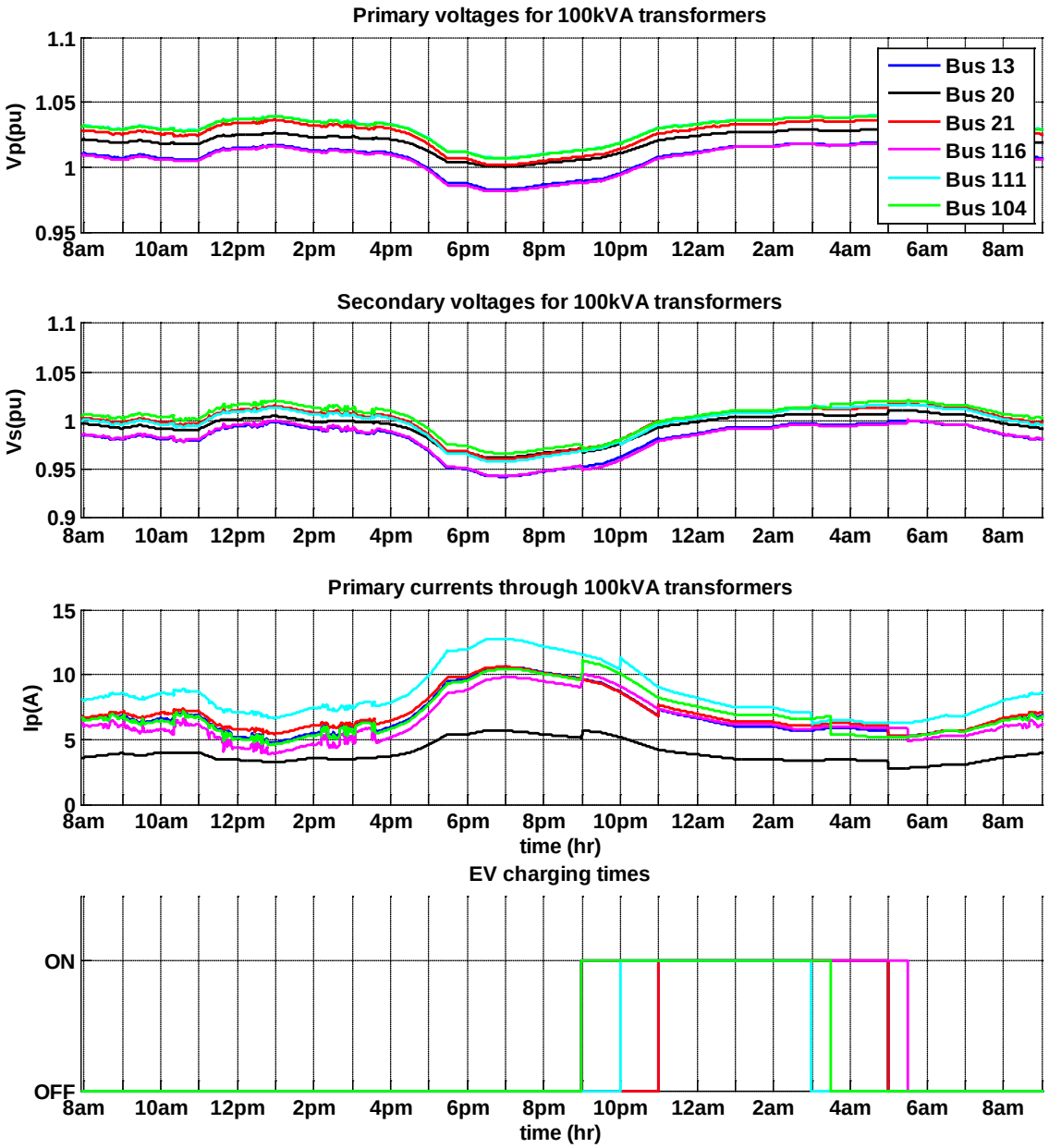

Figure 36 – Primary and secondary voltages and current at 100kVA transformers (controlled charging)

3.5 *Online - Closed Loop Operation of PEV Simulator with Grid Simulator*

This test verified operation of the closed loop and ability to communicate between the RTDS and the power hardware in the loop (PHIL): Level 2 PEV simulator and Grid simulator. The schematic diagram of the test setup is shown in *Figure 37*. Tests at different charging levels were performed to determine single level 2 PEV simulator operation.

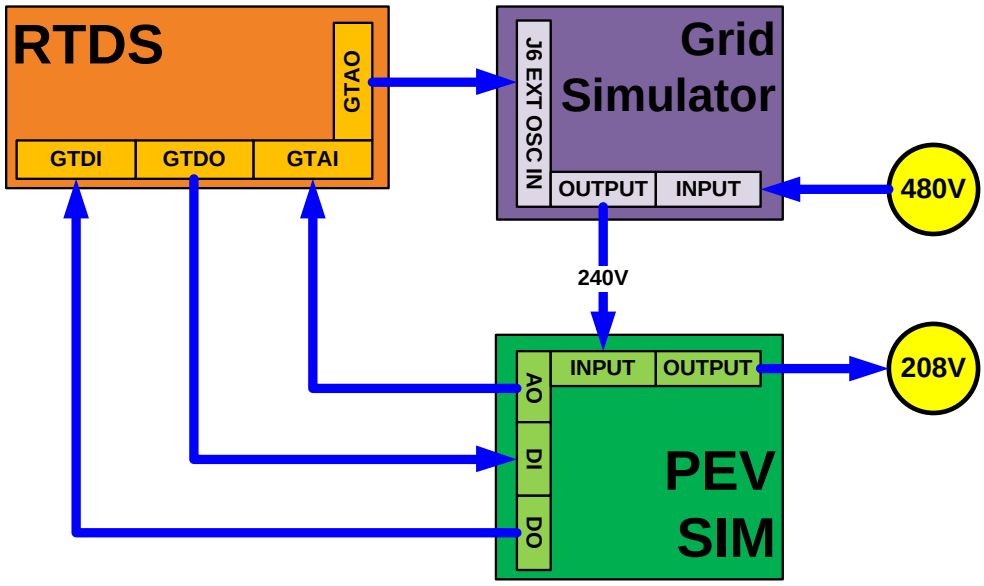

Figure 37 – RTDS hardware in loop setup for testing PEV charging impact

A 67 kVA grid simulator was used to amplify the secondary voltage measurement and feed into the PEV simulator. The secondary voltage was provided by an RTDS analog card as a signal in +/-10 V range and corresponded to the voltage at a selected service transformer from the simulated circuit under study. The grid simulator acted as a linear amplifier with a fixed gain to convert the low level signal to a 240 V range (variable) for the PEV simulator. The effects of circuit voltage changes (e.g. due to load or local generation variations and/or capacitor switching transients) were reflected in the secondary measurements.

The PEV simulator operated with the 240 V voltage from the grid simulator. Based on the selected charging level and charging profile, the charging current measurements from PEV simulator were determined and fed back to the RTDS as low level signals.

RTDS used the feedback current and injected them into the system through service transformer.

3.5.1 PEV profile with 3.5kW charging

The voltage and current for 3.5 kW PEV charging profile is shown in *Figure 38* below. The voltage and current were in phase. Voltage magnitude was proportional to the point of measurement. Current waveform had a minor distortion, which was considered insignificant.

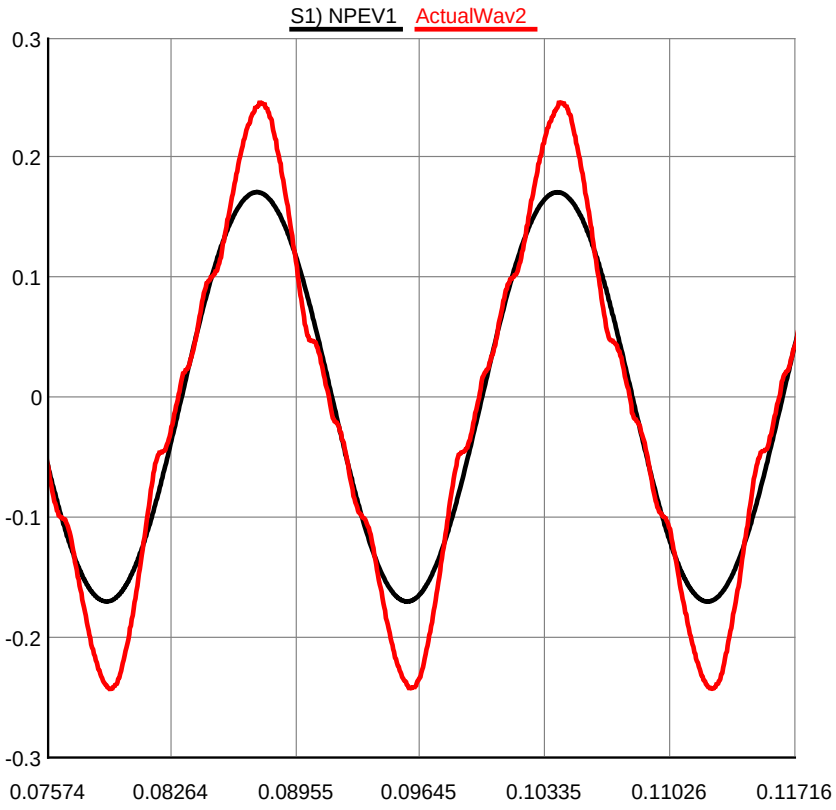

Figure 38 – PEV voltage (kV) and current (kA, scaled x10 for comparison)

For the purpose of verification, the injected current into the circuit was compared with the current measurement through the associated service transformer, assuming no load on the transformer. From the plot in *Figure 39* below, it was seen that the current injection from the EV measurements were accurately applied to the modeling environment.

The snapshot from the corresponding HMI screen for the test case and measurements are shown in *Figure 40* and *Figure 41*.

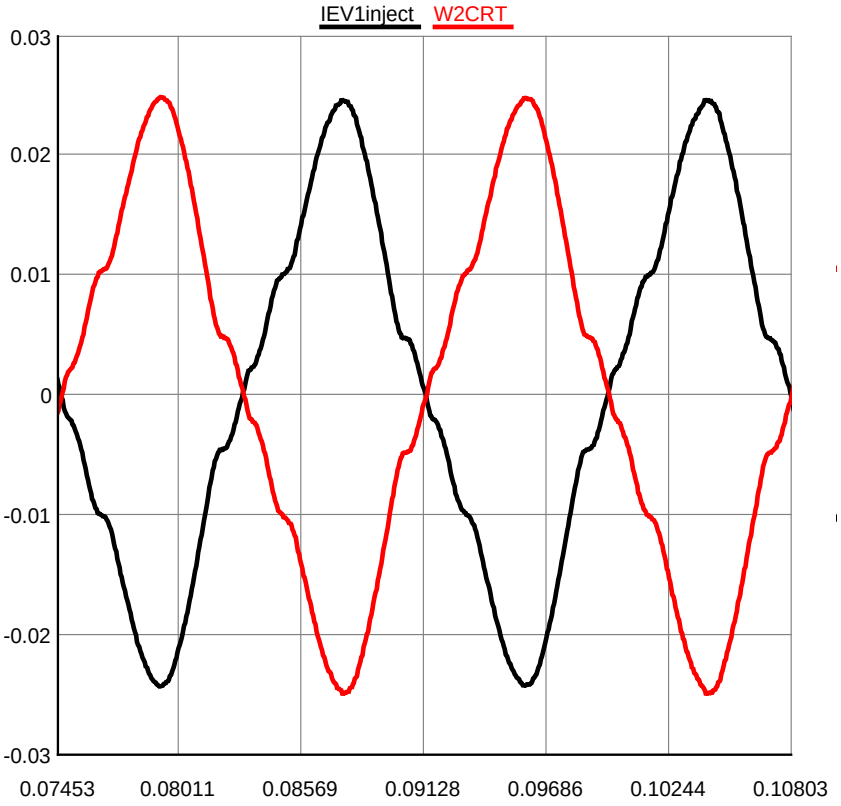

Figure 39 – Service transformer current (red) and PEV charging current (black) in kA

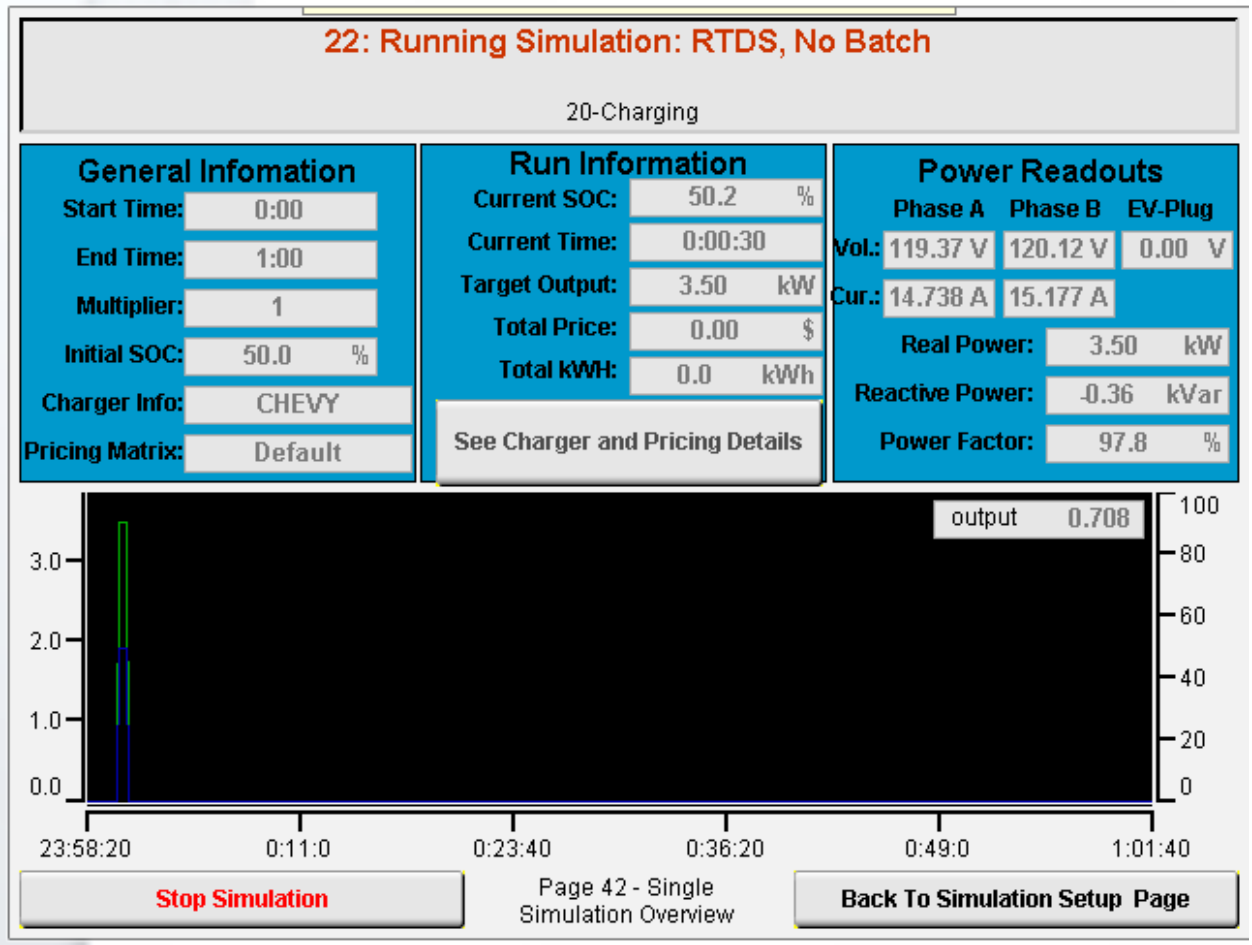

Figure 40 – Snapshot of the PEV HMI screen for 3.5kW charger

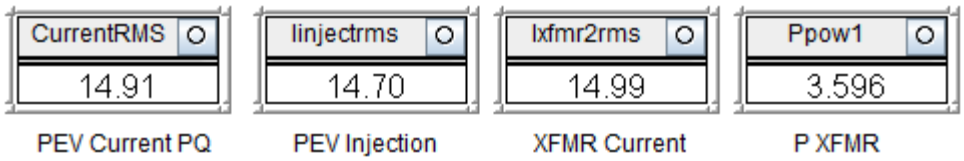

Figure 41 – RTDS measurement of currents (A) and transformer power (kW)

To verify the response time and dynamic behavior of the hardware in loop, the effect of a capacitor switching event was captured on PEV charging. Capacitor switching caused voltage divisions that impacted PEV charging current. A current ringing behavior was observed. As can be seen from the results, the dynamic aspect of capacitor switching phenomenon was properly captured in the test setup, as expected in the real life capacitor switching.

Due to a transient voltage spike, the EV charging current was also affected. Although power quality was not the primary focus of the study, it was observed that commonly occurring capacitor switching on a circuit can affect EV charging operation.

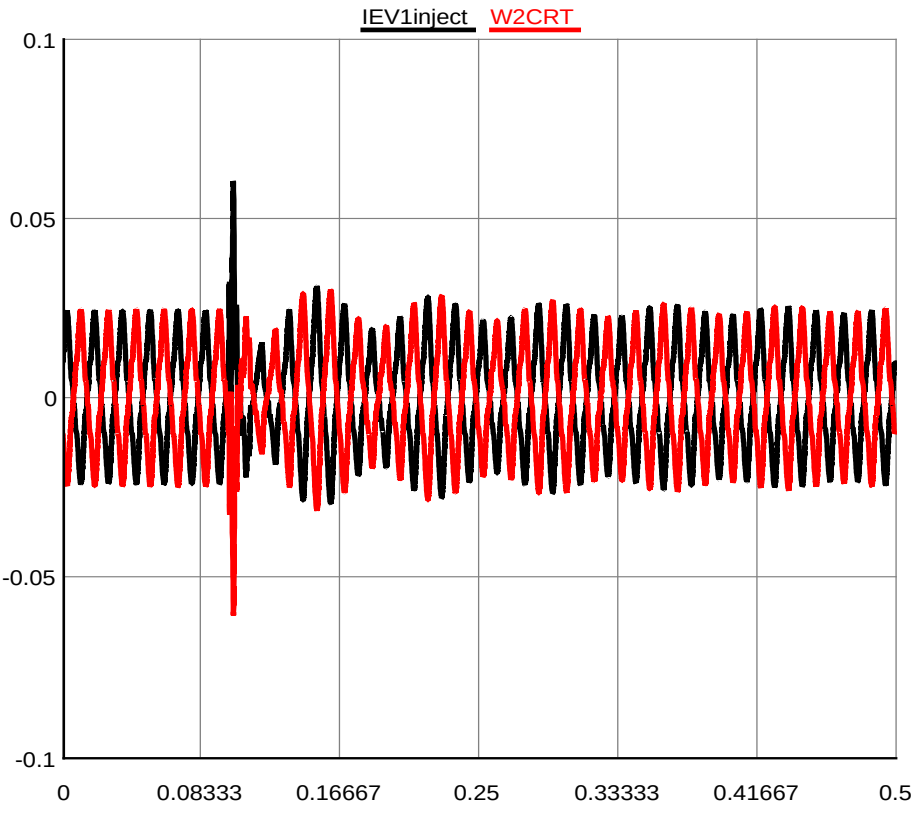

Figure 42 – PEV and transformer currents due to capacitor switching on

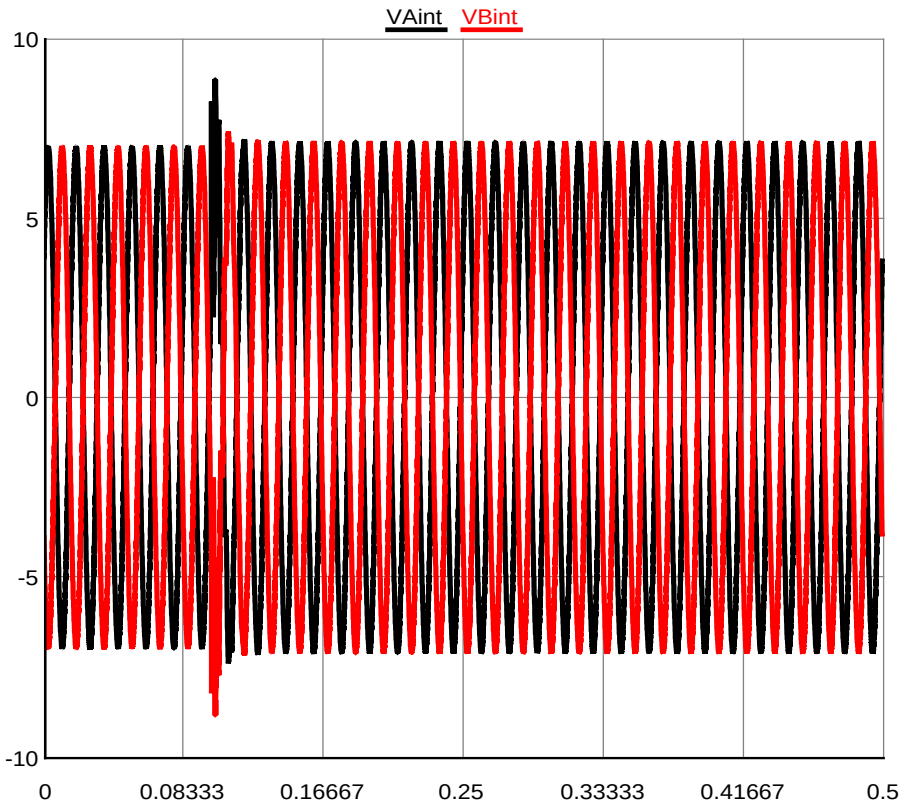

Figure 43 – PEV bus voltage (primary side) after capacitor switching

3.5.2 PEV profile with 5.2kW charging

The voltage and current for 5.2 kW PEV charging profile is shown in figure below for verification of the hardware in loop test setup.

Similarly, the current injection into the service transformer as part of the model and input to RTDS are shown in *Figure 45*. A snapshot of the HMI screen for verification of the test case is also shown in *Figure 46*.

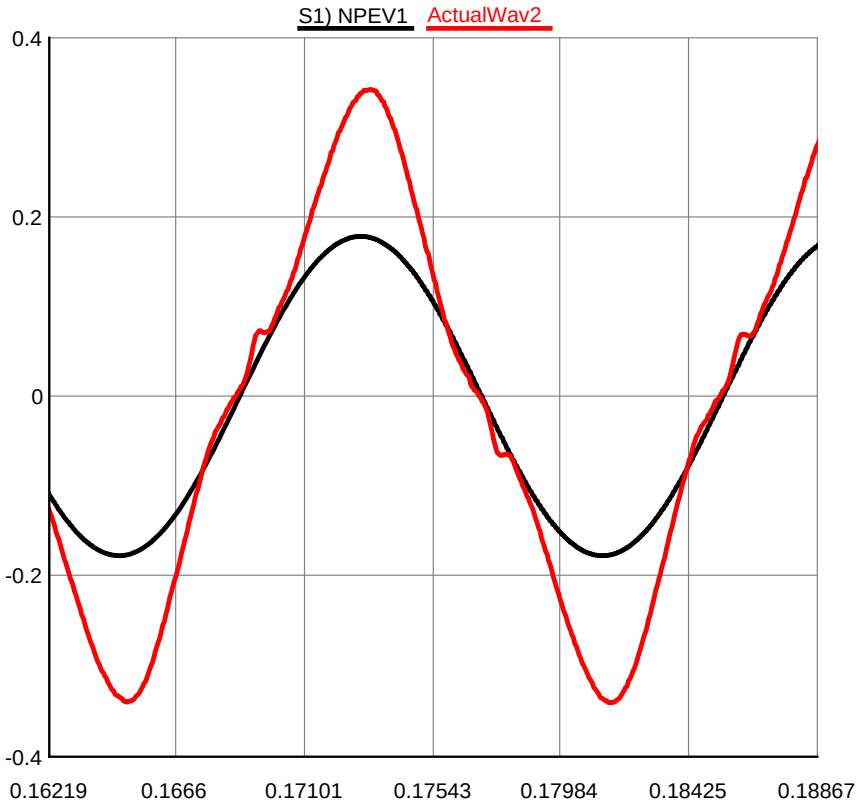

Figure 44 – PEV voltage (kV) and current (kA, scaled x10 for comparison)

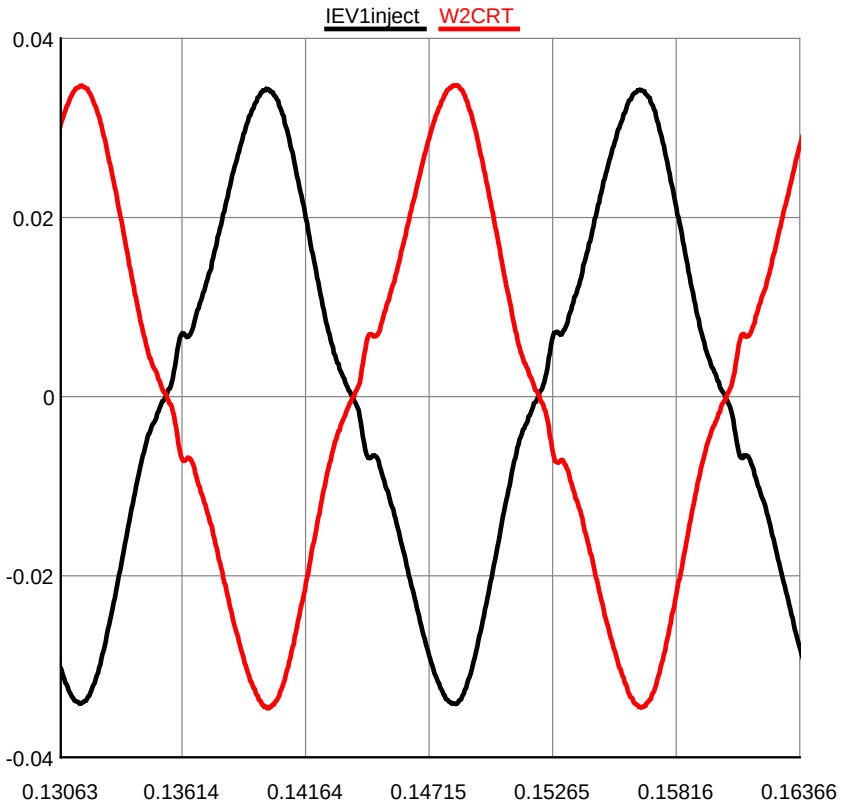

Figure 45 – Service transformer current (red) and PEV charging current (black) in kA

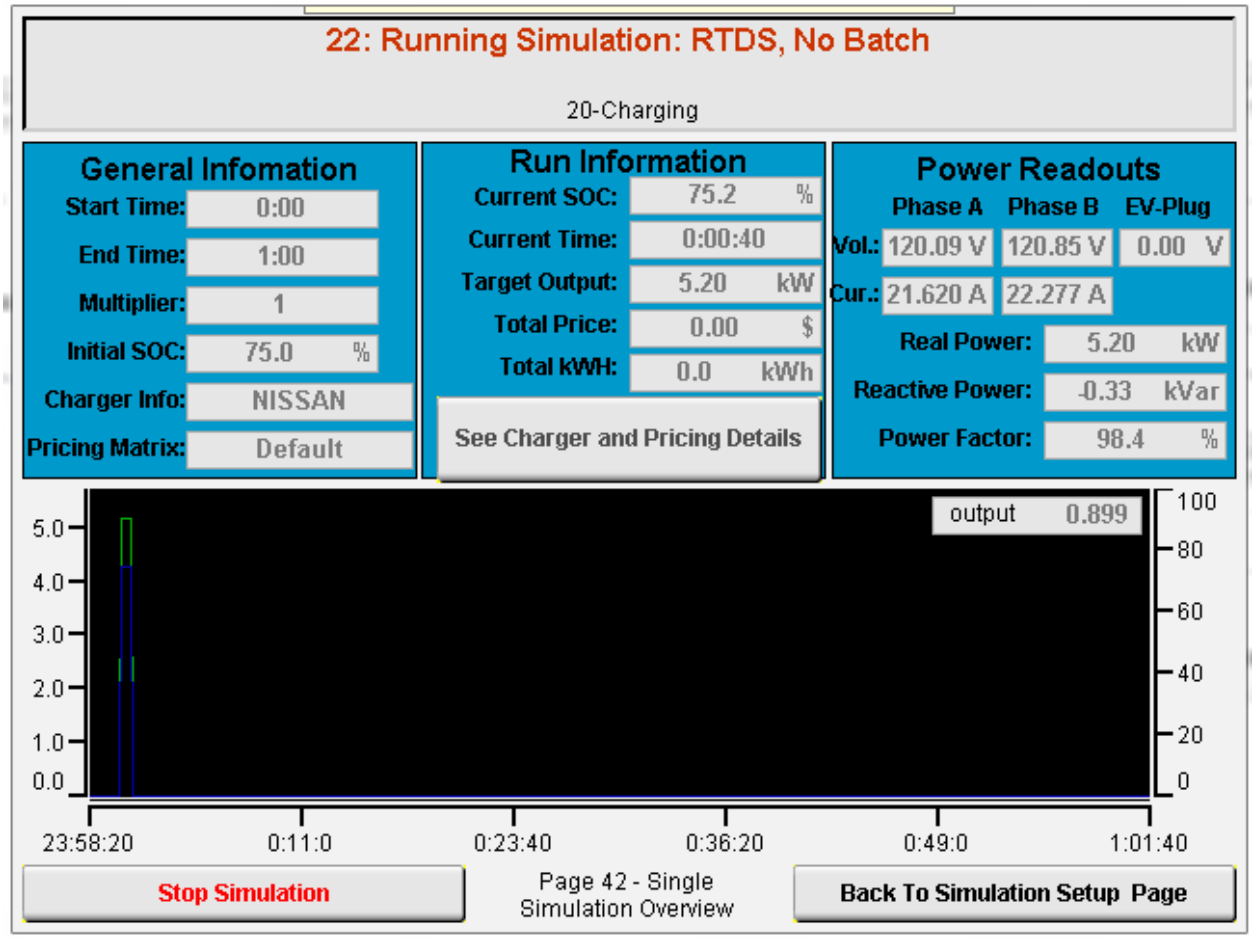

Figure 46 – Snapshot of the PEV HMI screen for 5.2kW charger

3.5.3 PEV profile with 8.7kW charging

The voltage and current for 8.7 kW PEV charging profile is shown in *Figure 47* below for verification of the hardware in loop test setup.

Similarly, the current injection into the service transformer as part of the model and input to RTDS are shown in *Figure 48*. A snapshot of the HMI screen for verification of the test case is also shown in *Figure 49*.

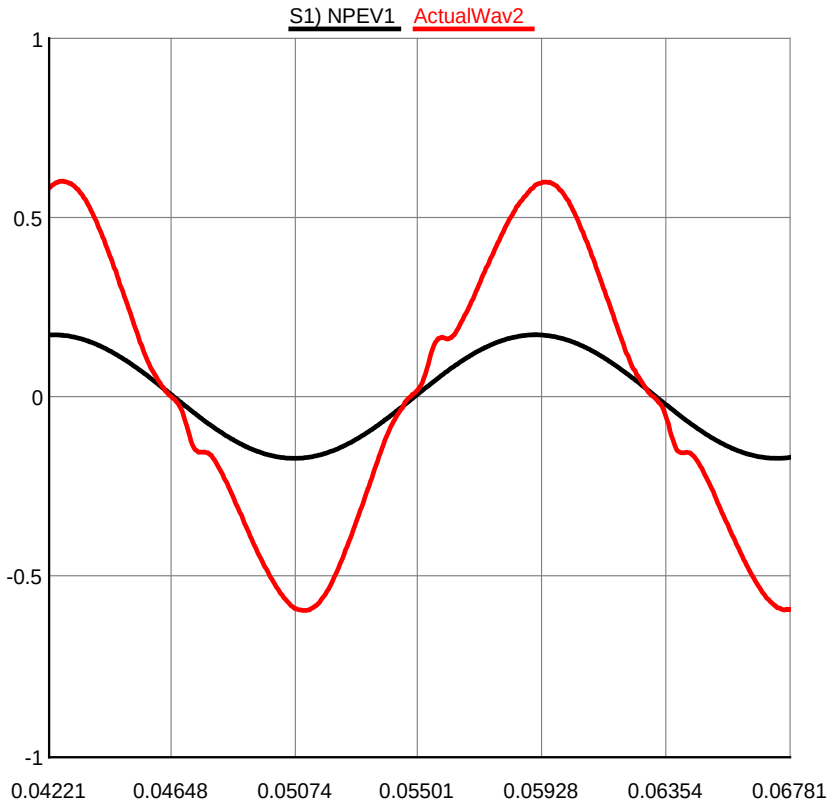

Figure 47 – PEV voltage (kV) and current (kA, scaled x10 for comparison)

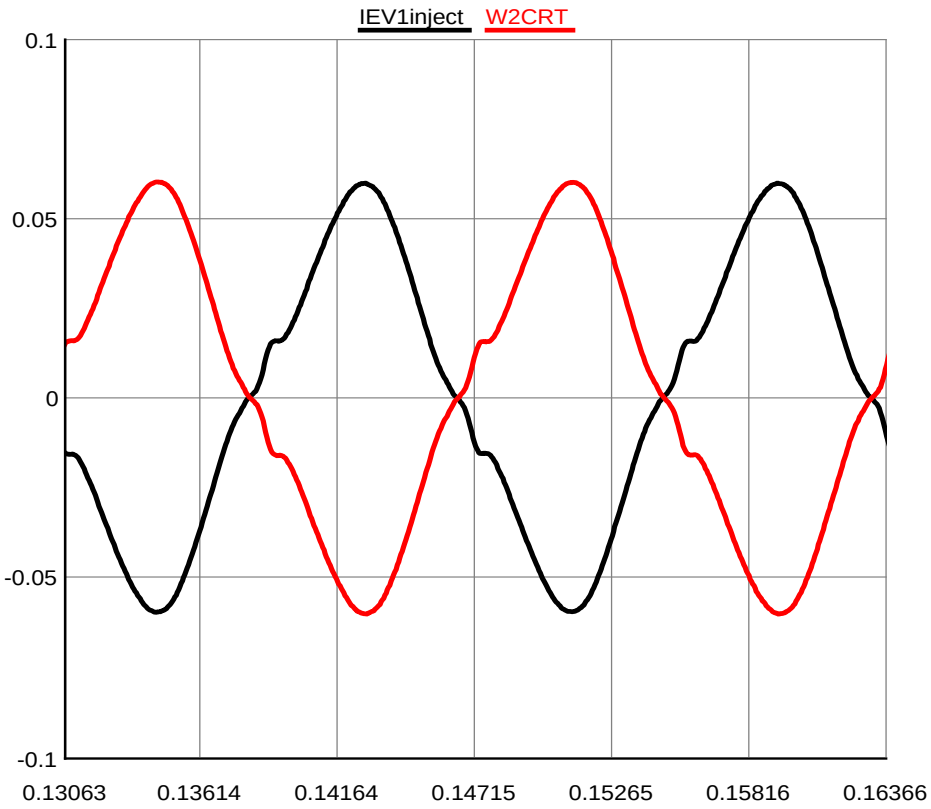

Figure 48 – Service transformer current (red) and PEV charging current (black) in kA

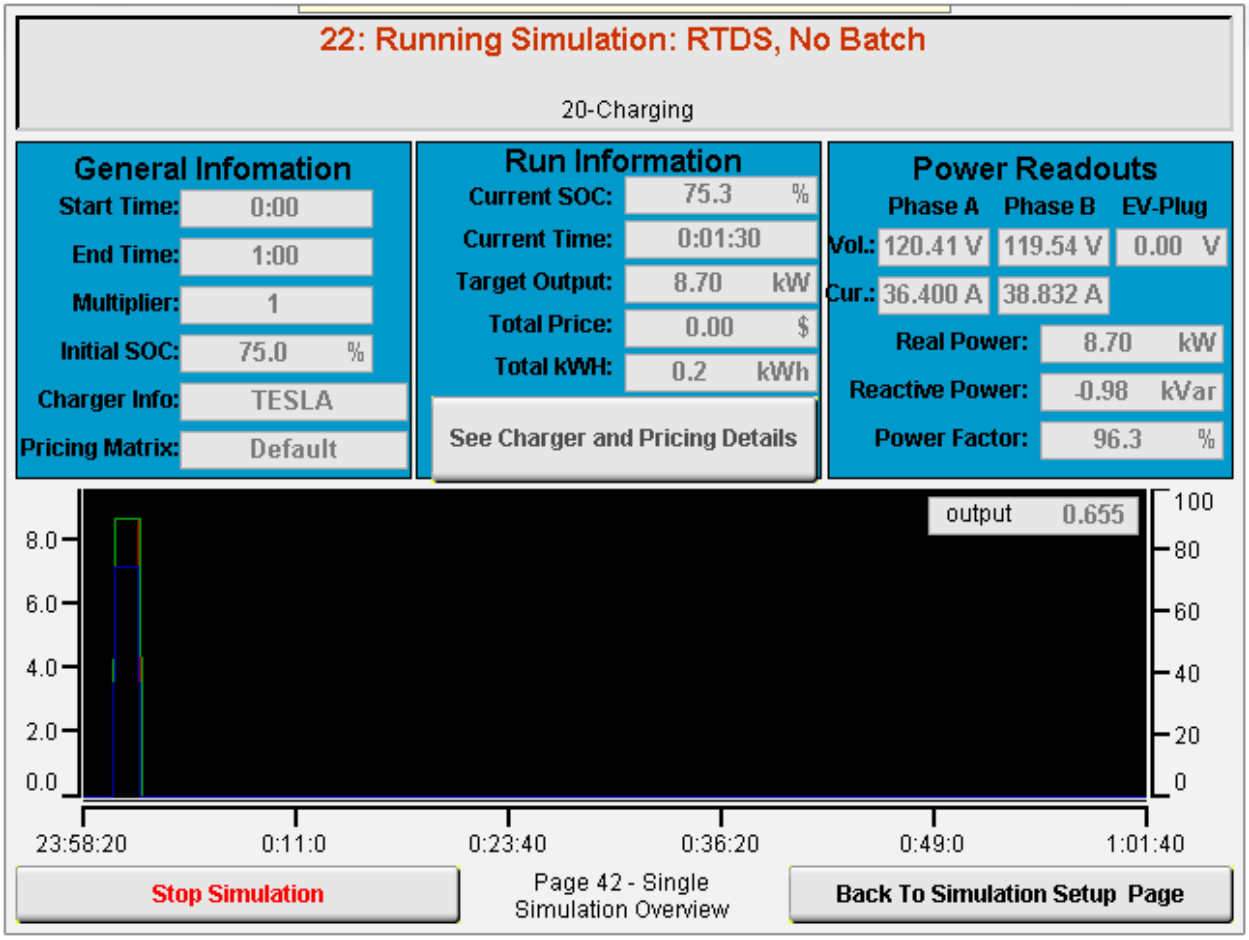

Figure 49 – Snapshot of the PEV HMI screen for 8.7kW charger

3.5.4 PEV profile with 9.6kW charging

The voltage and currents for 9.6 kW PEV charging profile is shown in *Figure 50* below for verification of the hardware in loop test setup.

Similarly, the current injection into the service transformer as part of the model and input to RTDS are shown in *Figure 51*. A snapshot of the HMI screen for verification of the test case is also shown in *Figure 52*.

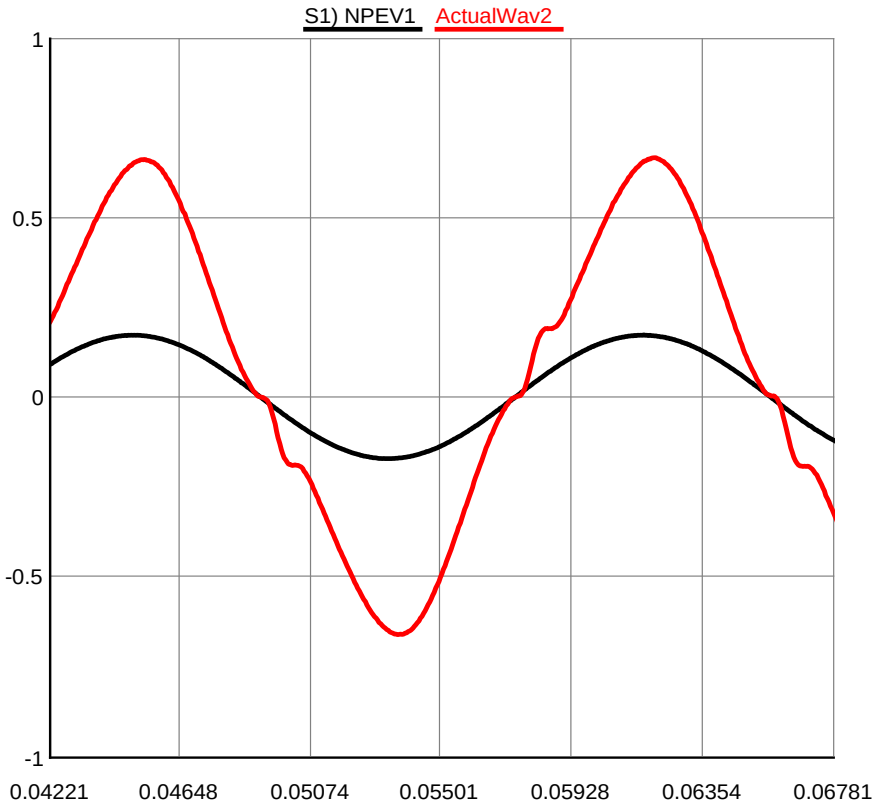

Figure 50 – PEV voltage (kV) and current (kA, scaled x10 for comparison)

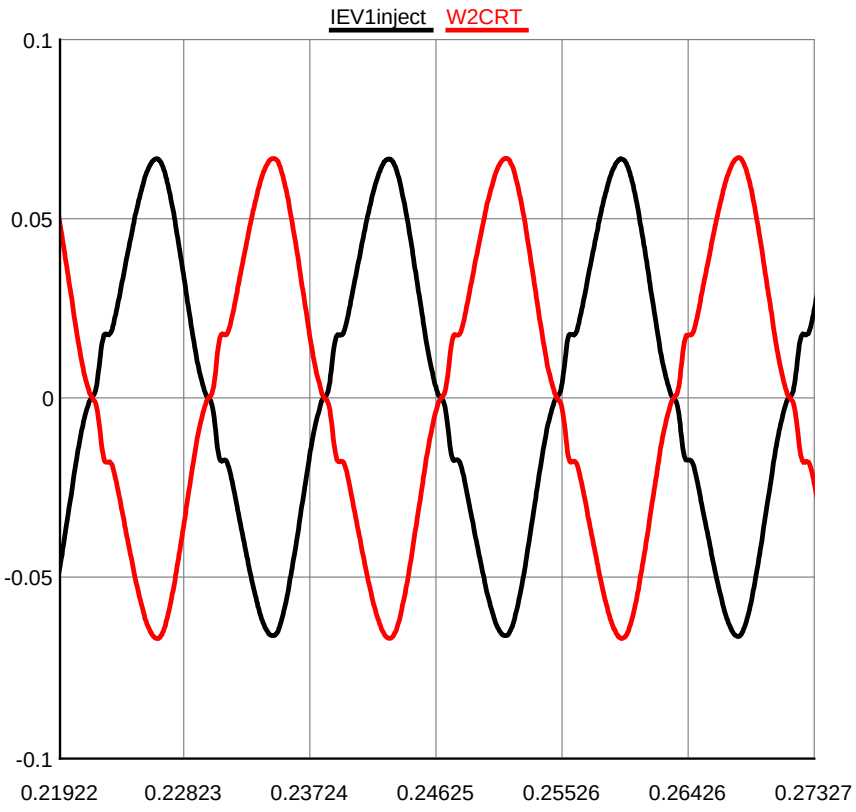

Figure 51 – Service transformer current (red) and PEV charging current (black) in kA

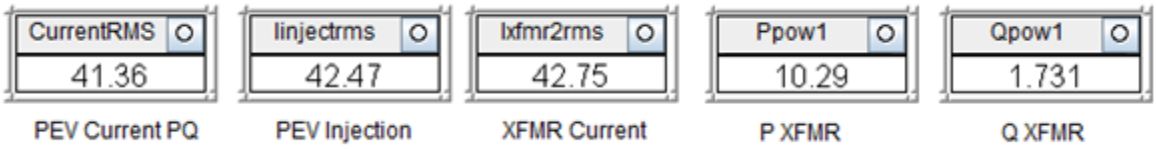

Figure 52 – RTDS measurement of currents (A) and transformer power (kW)

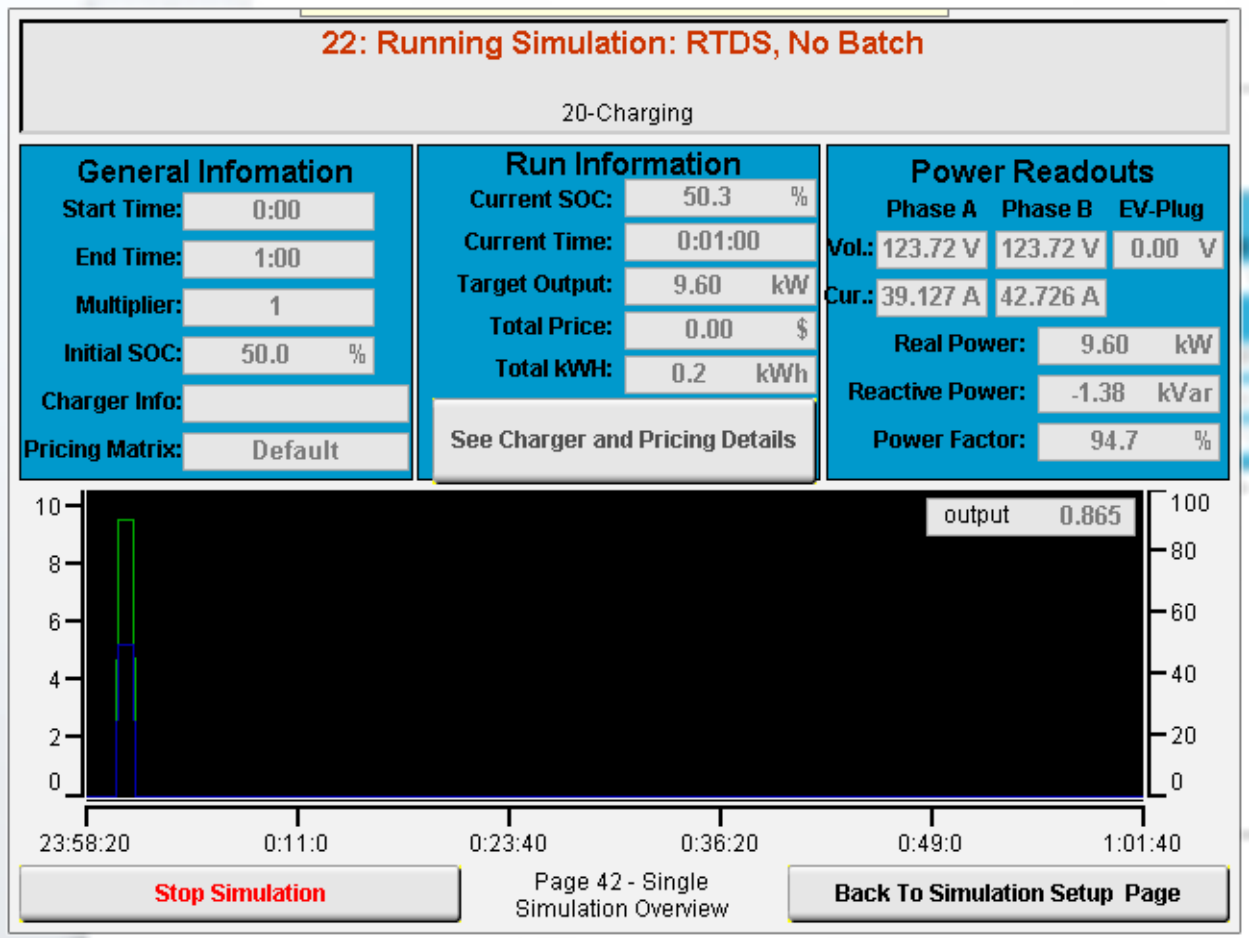

Figure 53 – Snapshot of the PEV HMI screen for 9.6kW charger

3.6 *Online – Single EV on circuit (15 minutes real time)*

These tests included the PEV simulator and Grid simulator operating in conjunction with the RTDS, and involve the connection of one EV customer (at Bus 119) to the circuit. The voltage waveform sent to the Grid Simulator was measured on the secondary circuit of the selected location, Bus 119. The test was performed starting at both 12:00pm and 8:00pm.

3.6.1 Start at 12:00pm

The transformer current and loading for a start at 12:00pm are shown in *Figure 55*, and circuit and transformer voltages are shown in *Figure 54*. It was observed that the voltage was heavily affected by the load profile within the 15 minute interval of the test. The transformer currents and loading showed a decline due to the decrease in load profile over the 15 minute test interval. As expected, the circuit and transformer voltages showed a corresponding increase. The transformer voltages and currents are shown at the moment the EV was active in *Figure 56*. The combined effect of circuit load variations and additional EV charging demand caused about a 2.5% decrease in secondary voltages.

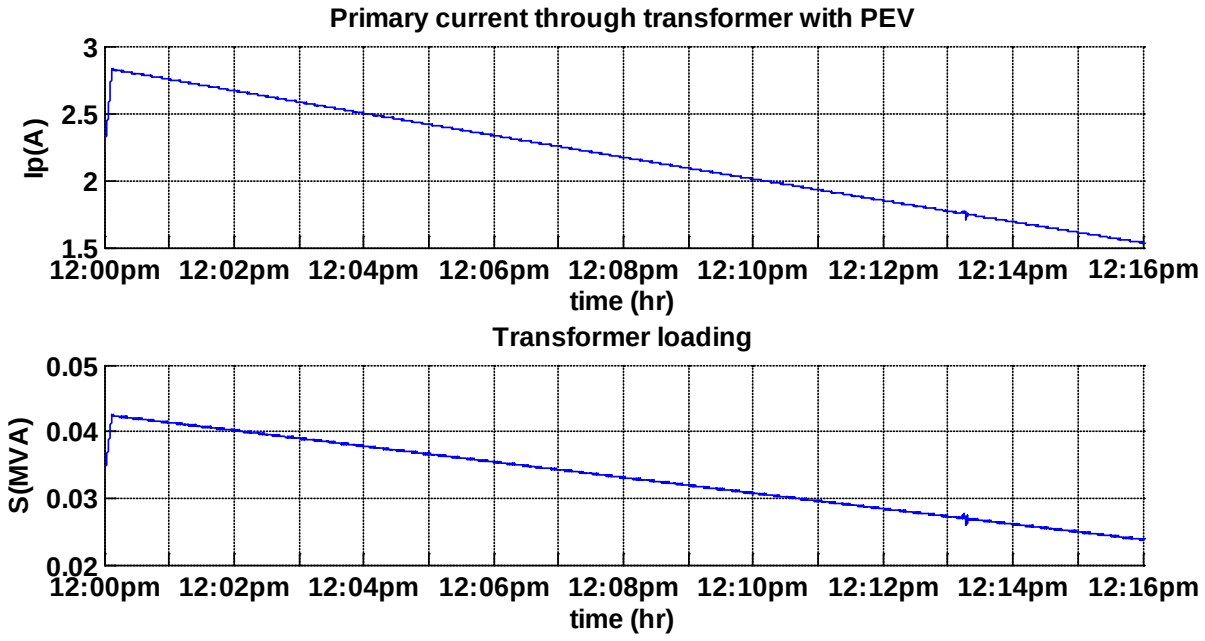

Figure 54 – Transformer current and loading for single EV at Bus 119 (12:00pm start)

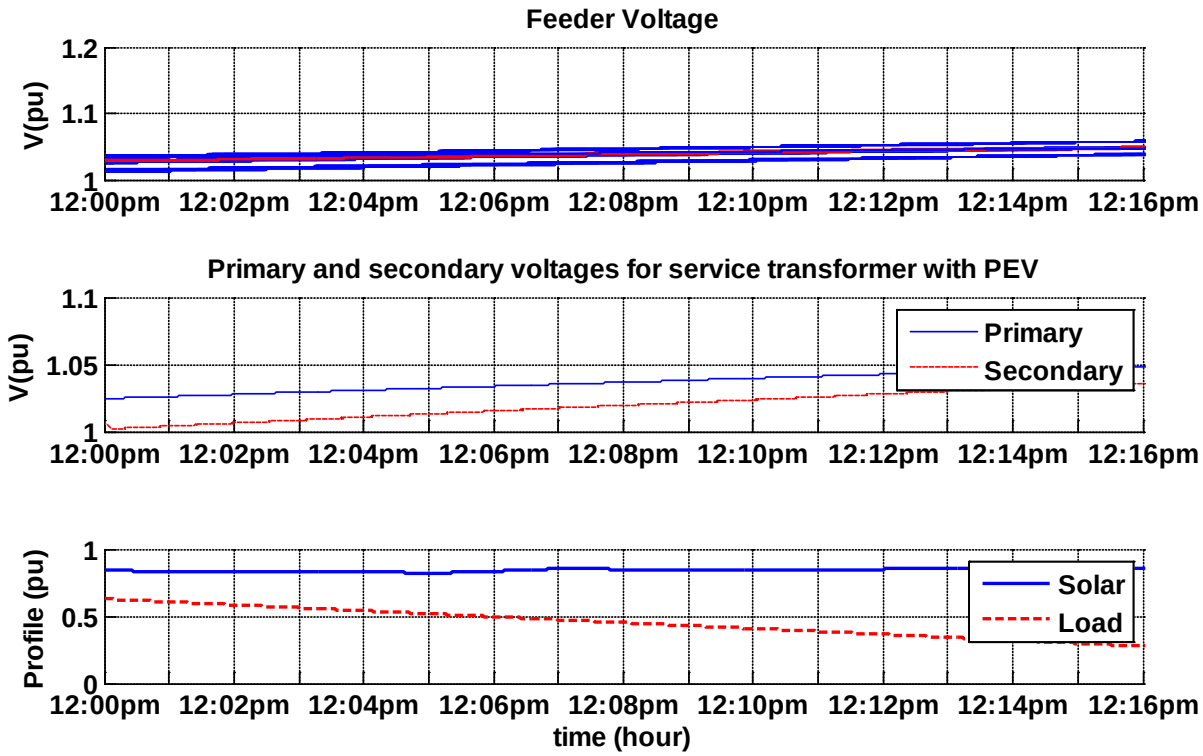

Figure 55 – Voltages at all circuit location and transformer locations for single EV at Bus 119 (12:00pm start)

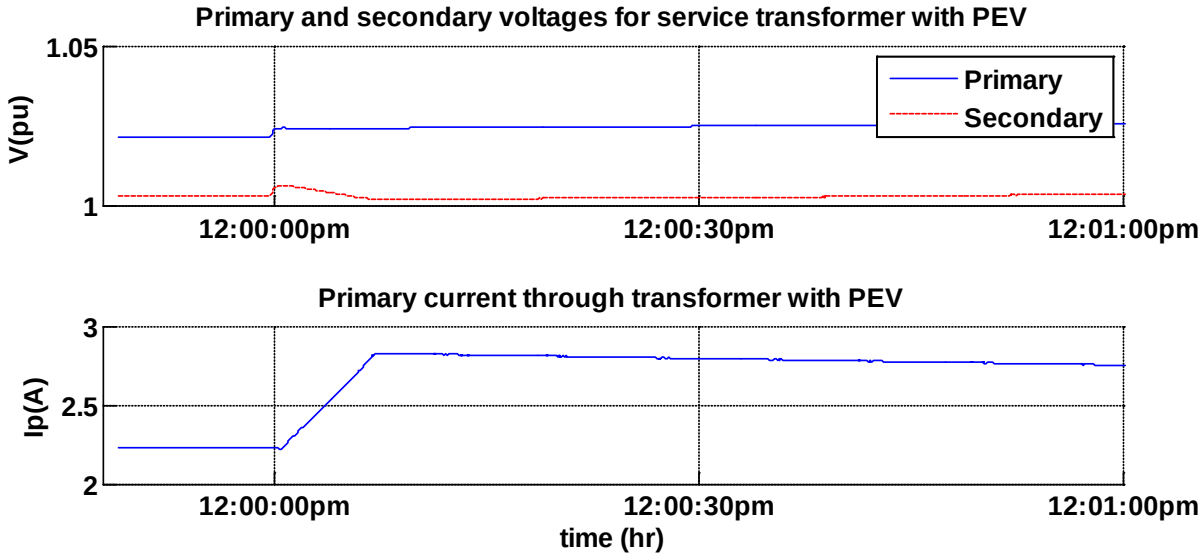

Figure 56 – Zoomed in transformer voltage and currents during EV startup at 12:00pm

3.6.2 Start at 8:00pm

The transformer current and loading for a start at 8:00pm are shown in *Figure 58*, and circuit and transformer voltages are shown in *Figure 57*. It was seen that the voltage was heavily affected by the load profile within the 15 minute interval of the selected test circuit. The transformer currents and loading showed a decline due to the decrease in load profile over the 15 minute interval. As expected, the circuit and transformer voltages showed a corresponding increase.

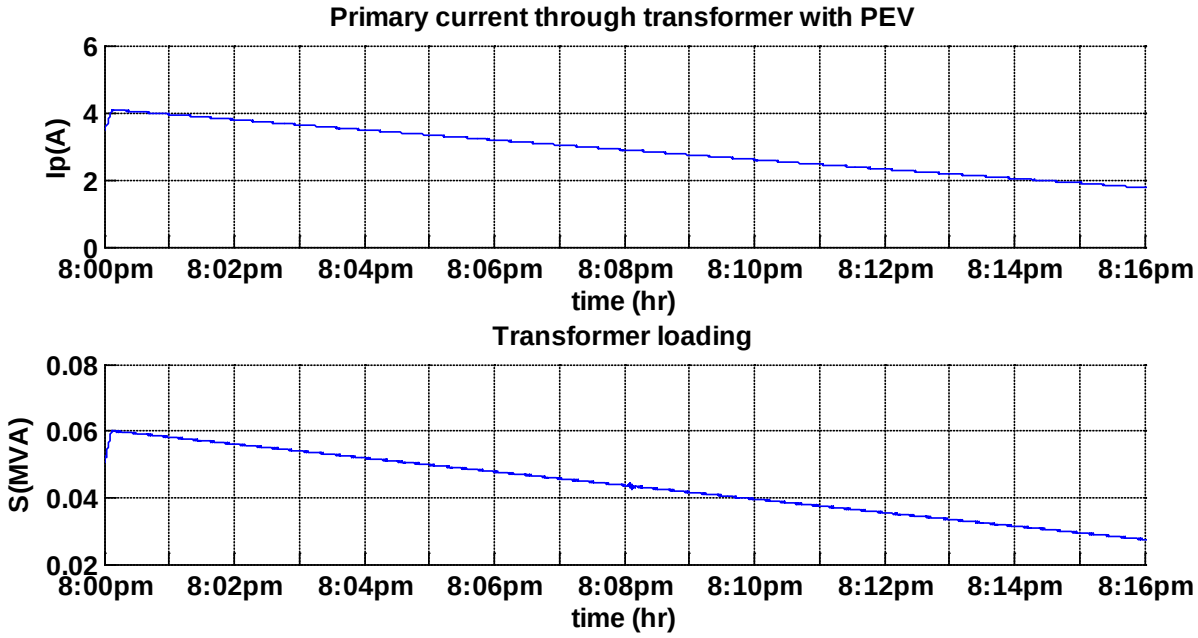

Figure 57 – Transformer current and loading for single EV at Bus 119 (8:00pm start)

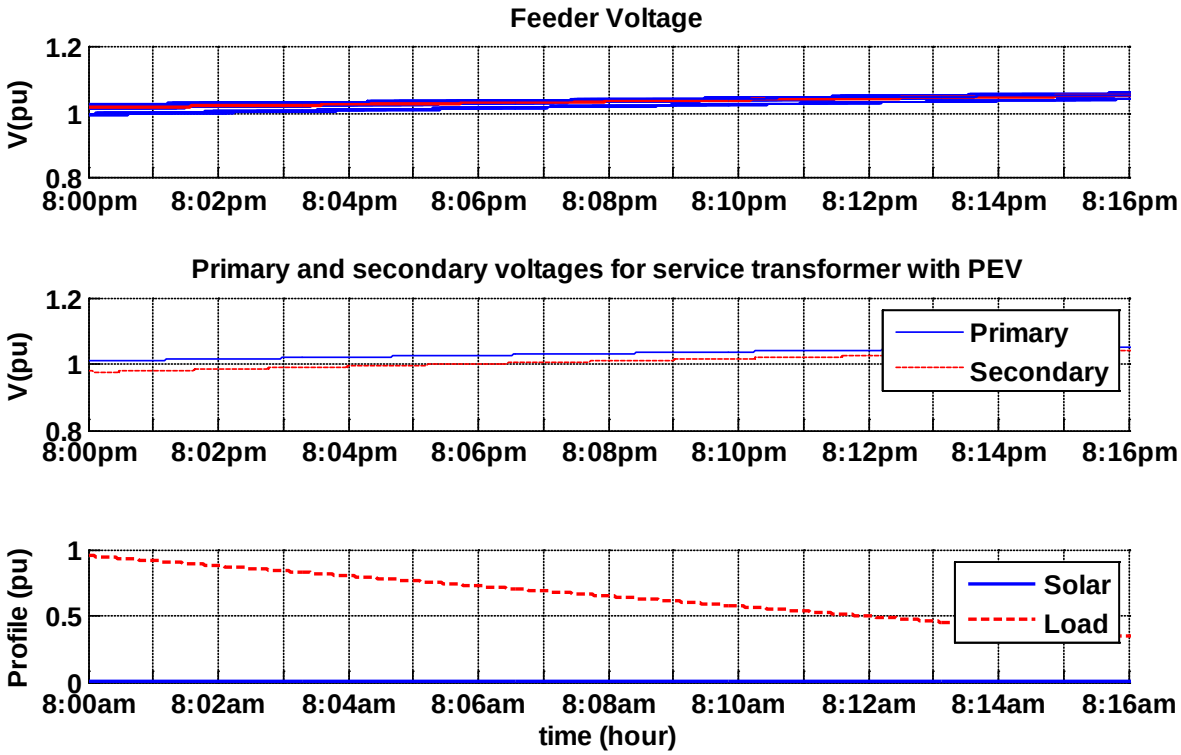

Figure 58 – Voltages at all circuit location and transformer locations for single EV at Bus 119 (8:00pm start)

3.7 *Online – Full system test – existing number of customers (15 minutes real time)*

This test covered the entire system, with all existing EV customers connected to Circuit A. The test was performed starting at both 12:00pm and 8:00pm. EV outputs were added at fourteen (14) existing customer locations. EV Set 1 (random distribution) defines the sizes and EVs are on for the entire 15 minute period. The details for EV size are given in ***Table 7***.

Table 7 – EV size for all existing customers (14)

	Transformer Parameters			Load and PV			EV Size
Bus #	XFMR kVA		Connection	Total Load		Total PV	Set 1
	Rated	Actual		kW	kVAR	kW	kW
13	100	88	A	69	12	9.8	3.3
15	50	41	AB	55	10	12.7	3.3
17	50	41	AB	55	9	6.0	5.8
20	100	82	AC	235	41		6.6
23	25	18	B	14	2		3.3
19	50	32	A	41	7	3.3	5.8
116	100	82	A	137	24	13.2	6.6
112	50	35	B	28	5	4.7	5.8
109	50	35	A	28	5	4.3	9.8
106	25	17	B	14	2		9.8
118A	50	41	AB	55	10	9.5	6.6
118B	50	46	BC	260	10	9.5	9.8
119	50	53	AB	42	7		6.6
121	25	24	C	19	3	5.4	5.8

3.7.1 Start at 12:00pm

Voltages for the entire circuit for uncontrolled charging are shown in *Figure 59*. Voltages for selected locations on each subsystem are also shown in *Figure 60*. Transformer voltages and currents are shown in *Figure 61* through *Figure 64*.

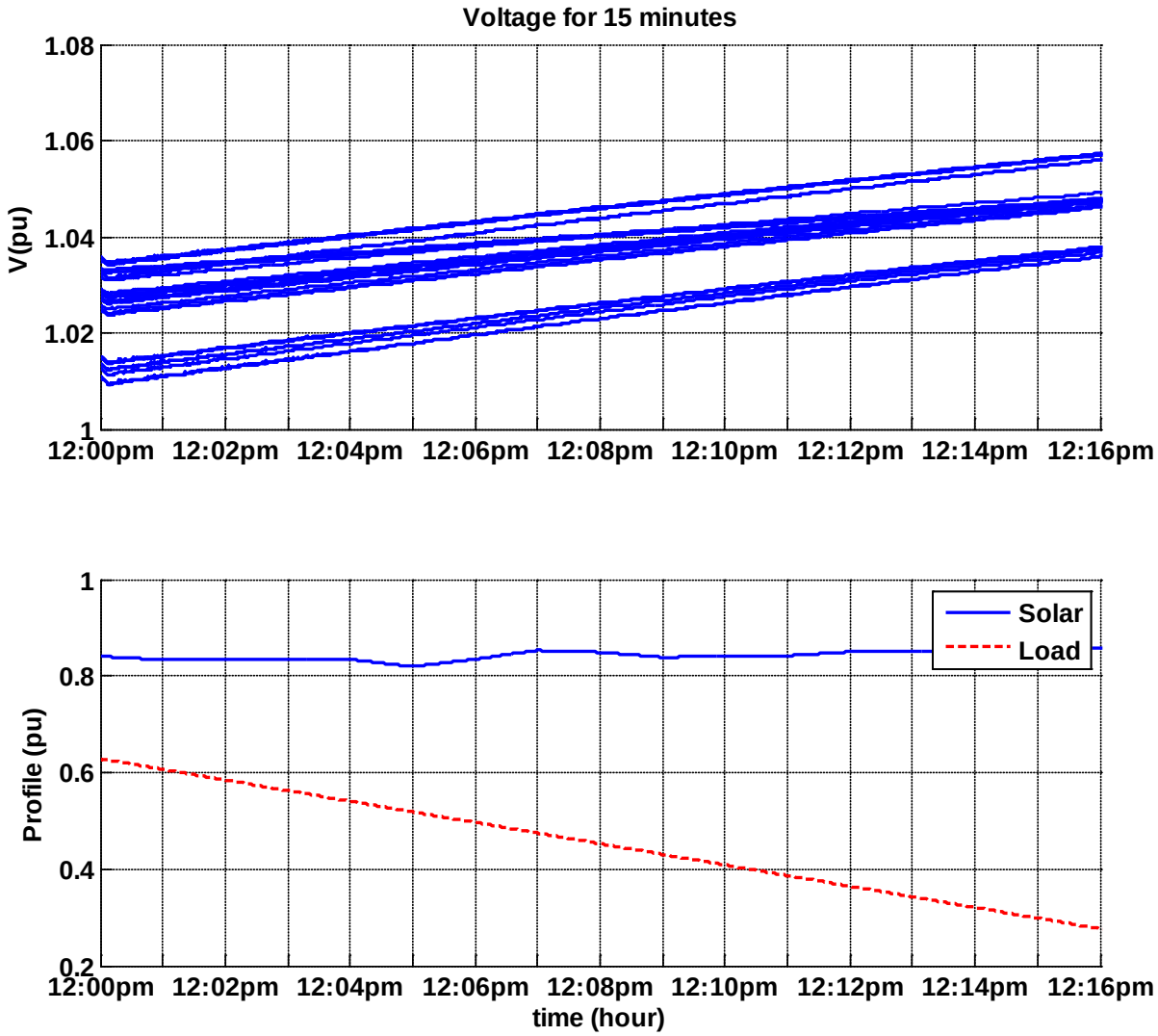

Figure 59 – Voltage at all circuit locations for varying load and PV profile (12:00pm start)

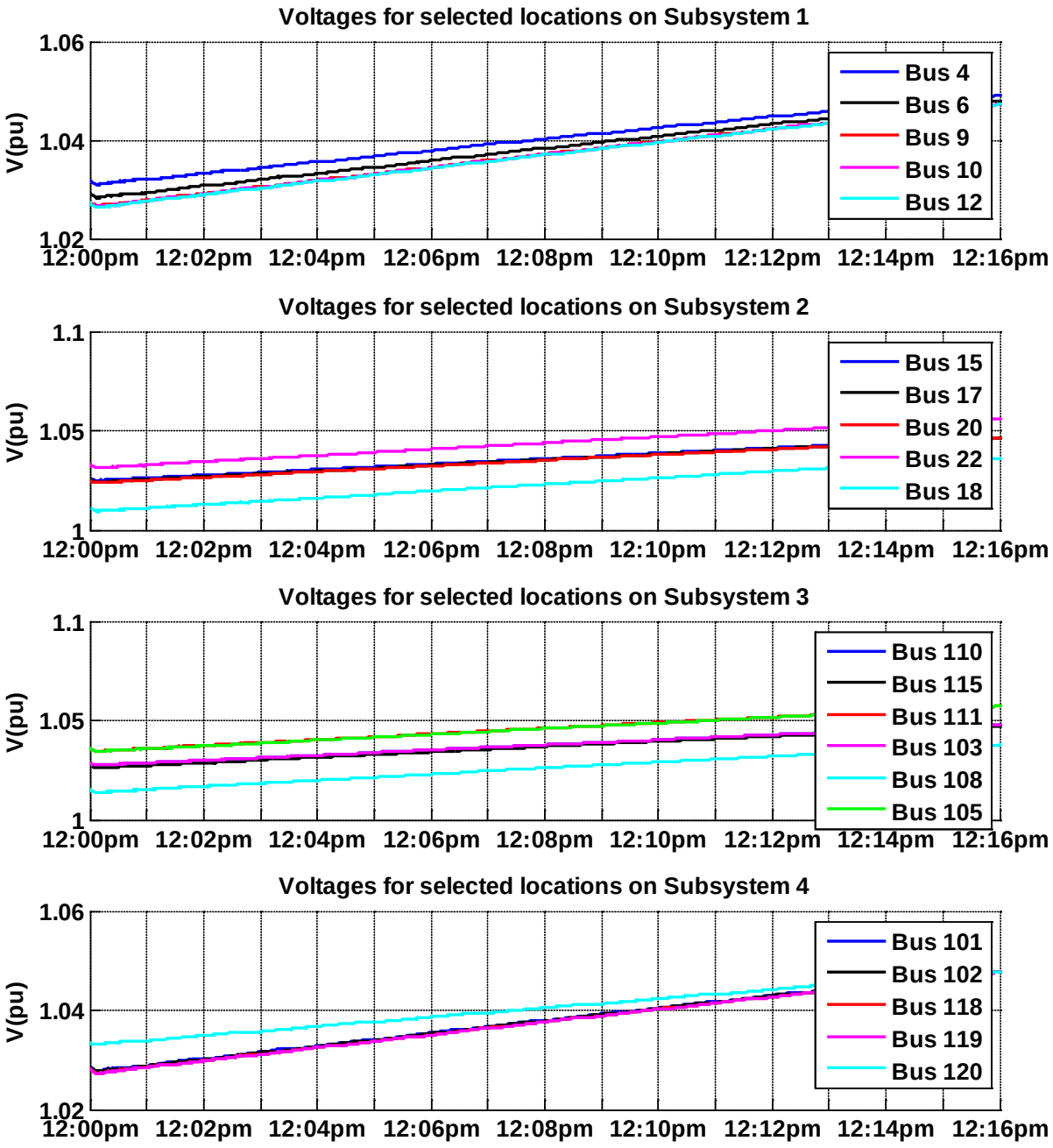

Figure 60 – Voltage at selected circuit locations for varying load and PV profile (12:00pm start)

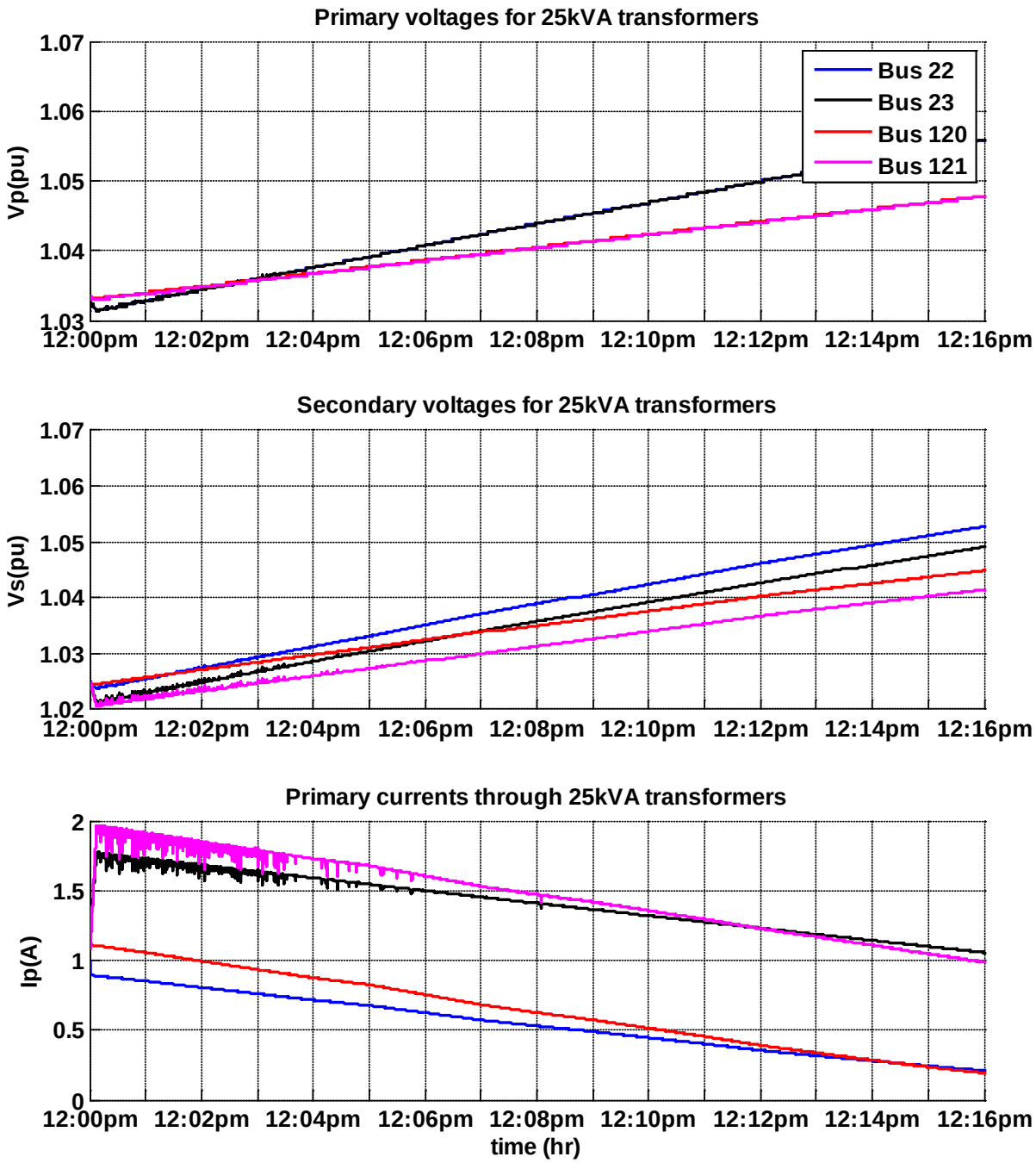

Figure 61 – Primary and secondary voltages and current at 25kVA transformers (12:00pm start)

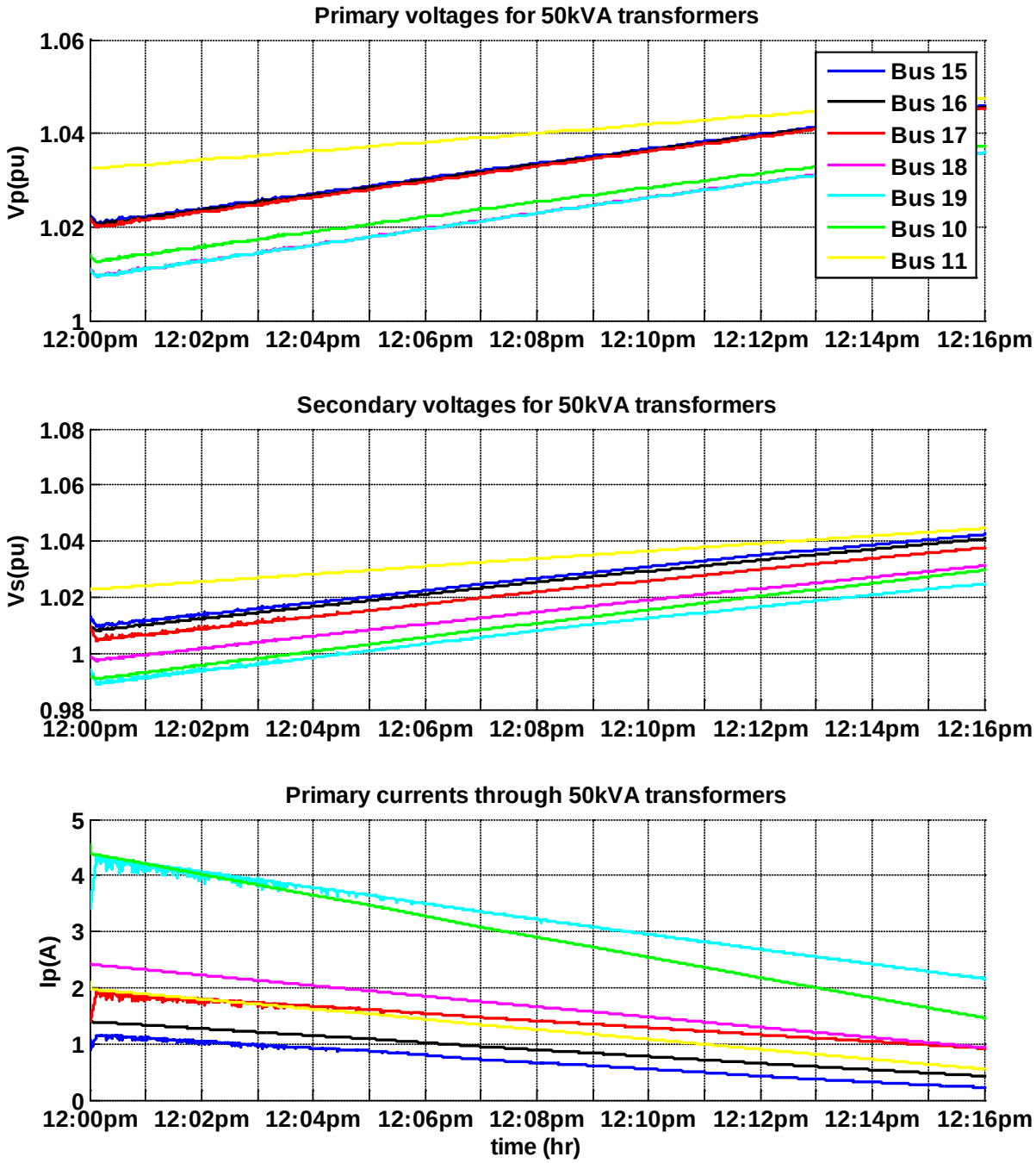

Figure 62 – Primary and secondary voltages and current at 50kVA transformers (12:00pm start)

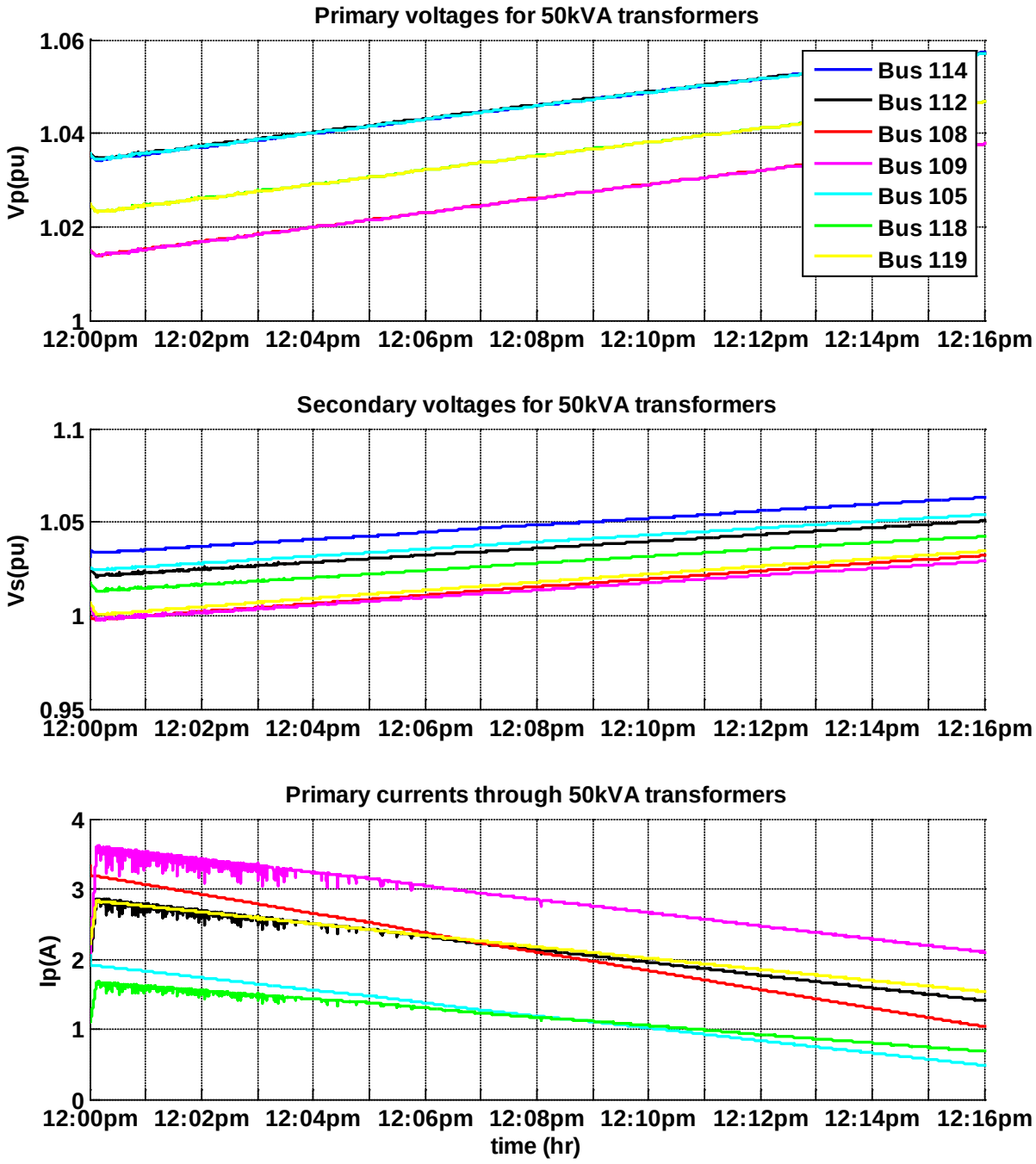

Figure 63 – Primary and secondary voltages and current at 50kVA transformers (12:00pm start)

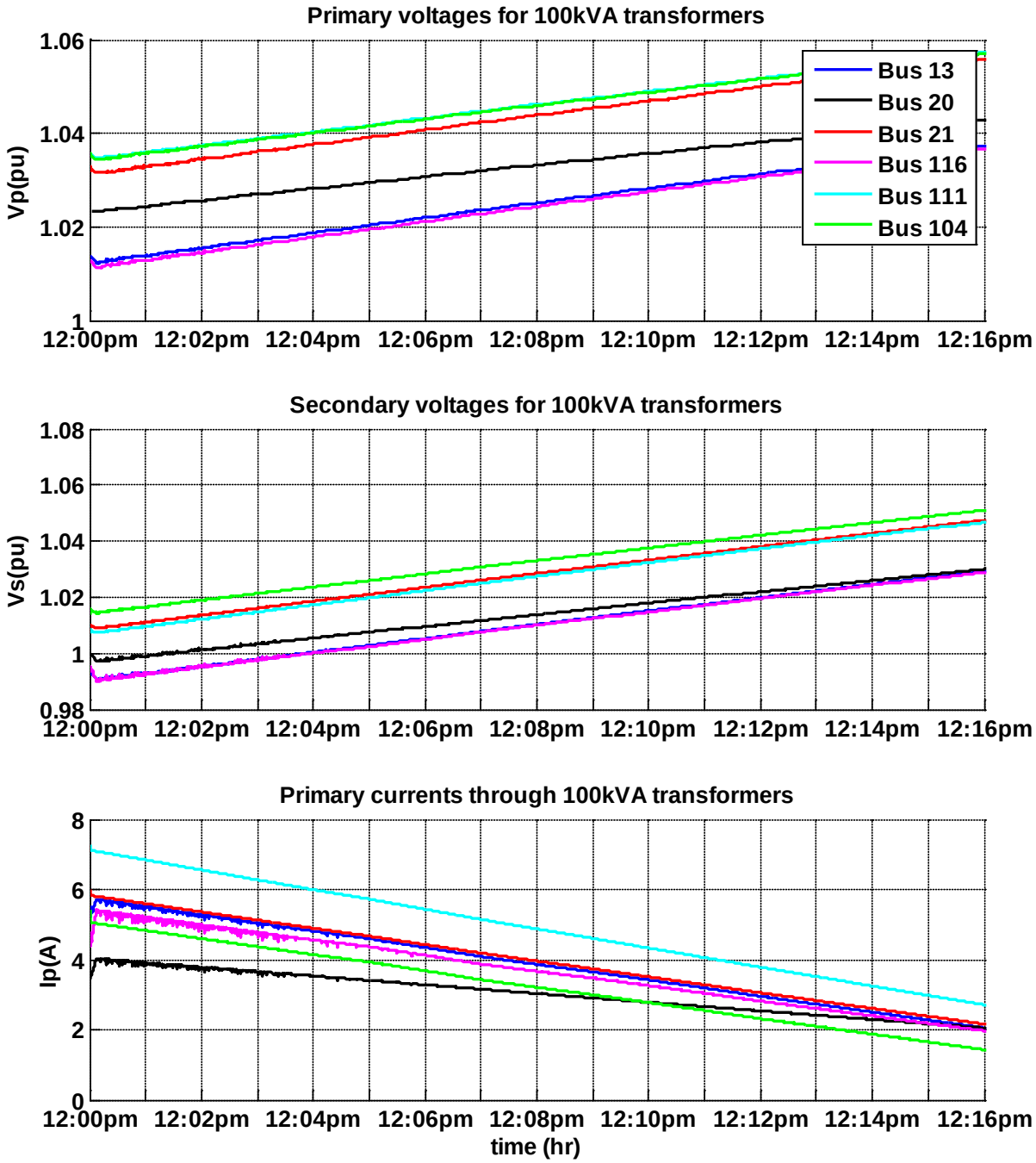

Figure 64 – Primary and secondary voltages and current at 100kVA transformers (12:00pm start)

3.7.1 Start at 8:00pm

Voltages for the entire circuit for uncontrolled charging are shown in *Figure 65*. Voltages for selected locations on each subsystem are shown in *Figure 66*. Transformer voltages and currents are shown in *Figure 67* through *Figure 70*.

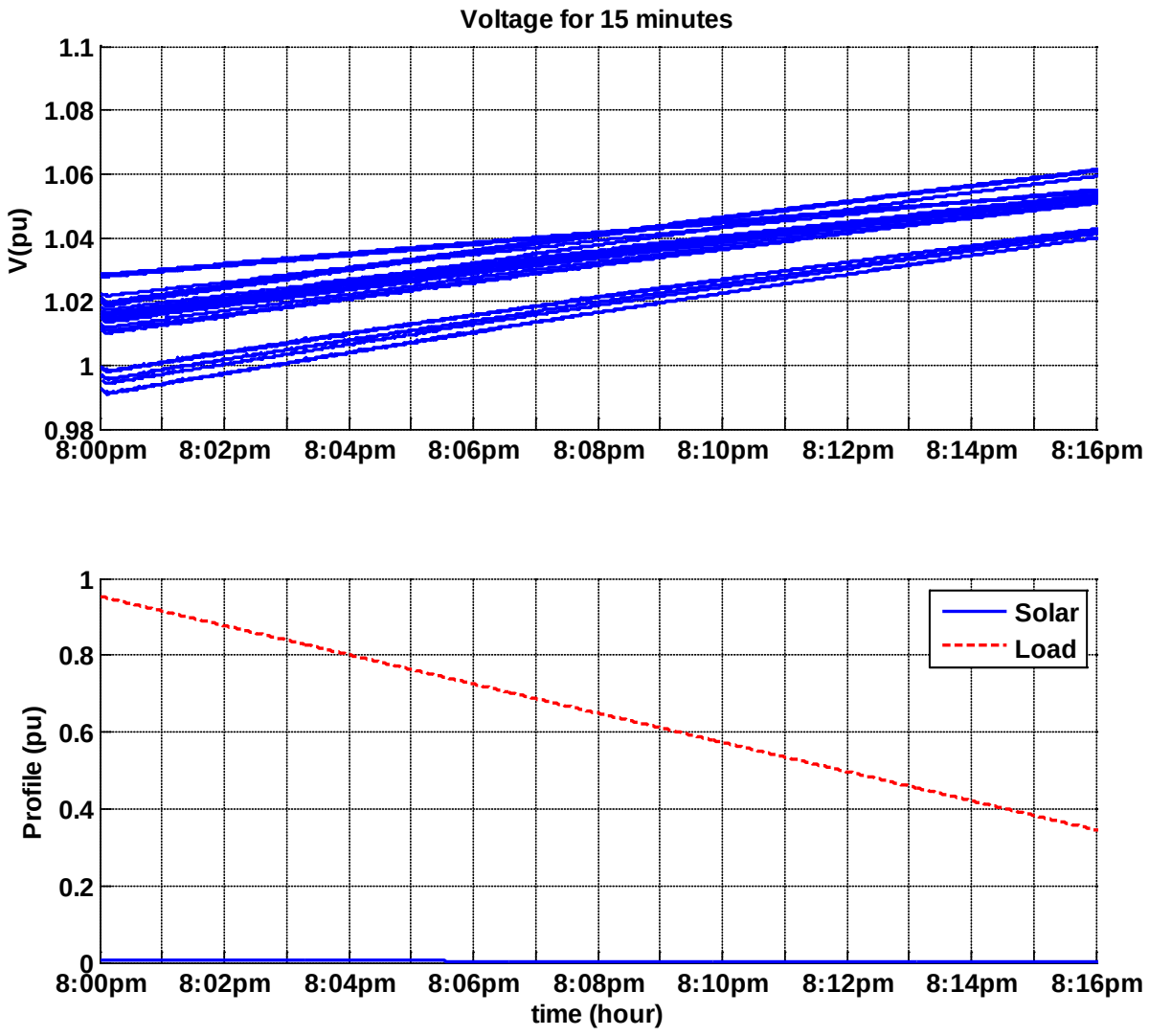

Figure 65 – Voltage at all circuit locations for varying load and PV profile (8:00pm start)

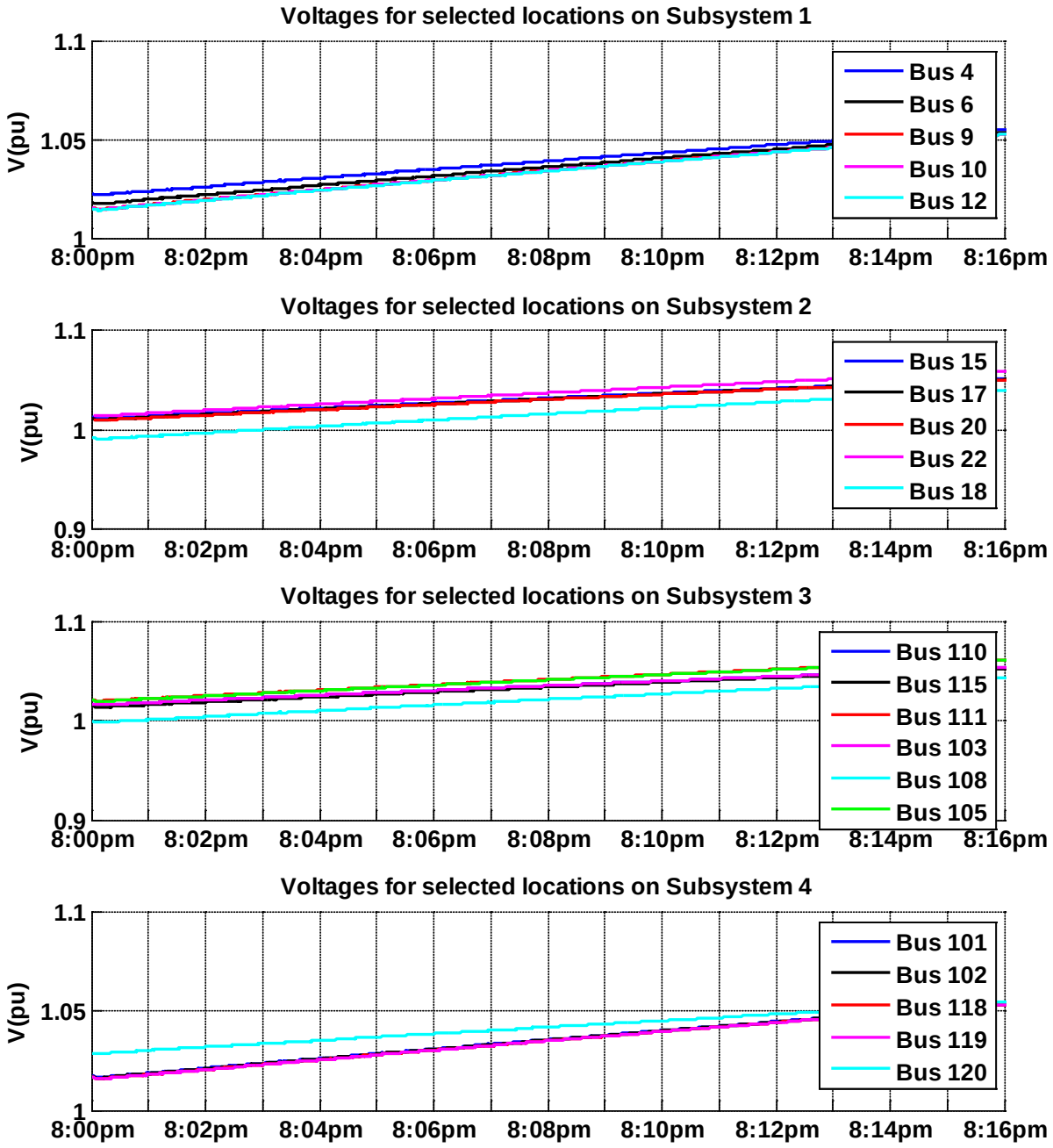

Figure 66 – Voltage at selected circuit locations for varying load and PV profile (8:00pm start)

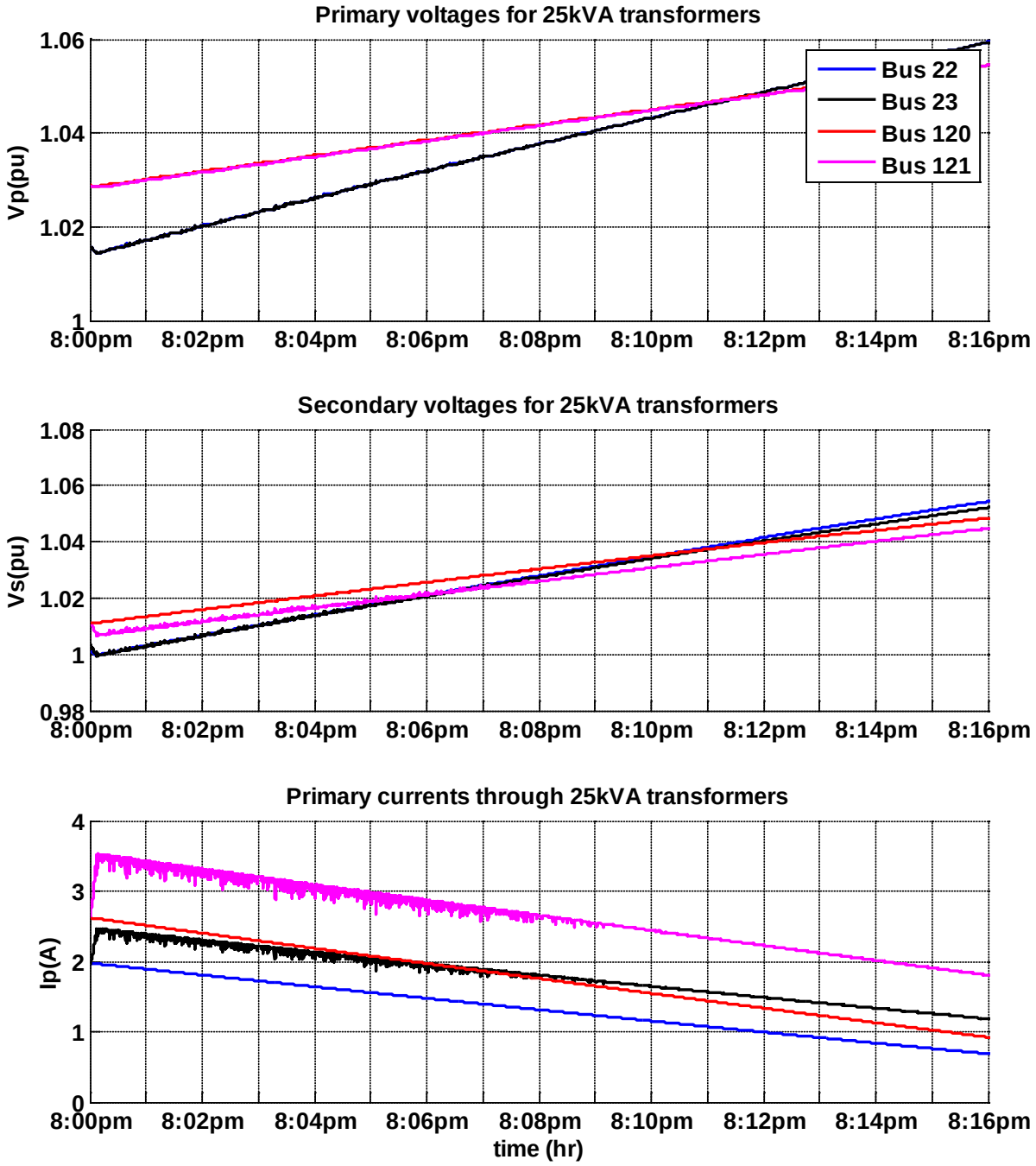

Figure 67 – Primary and secondary voltages and current at 25kVA transformers (8:00pm start)

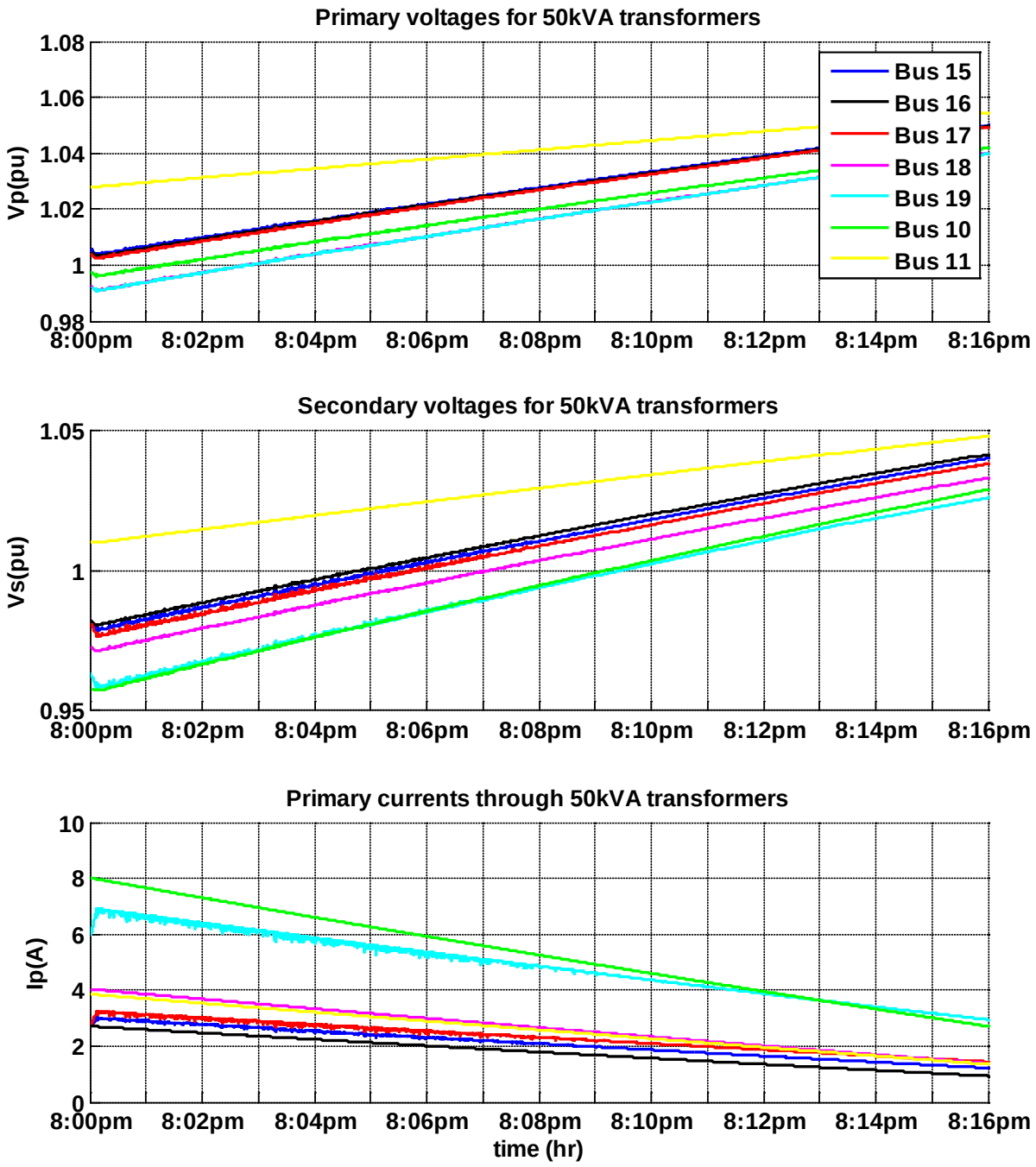

Figure 68 – Primary and secondary voltages and current at 50kVA transformers (8:00pm start)

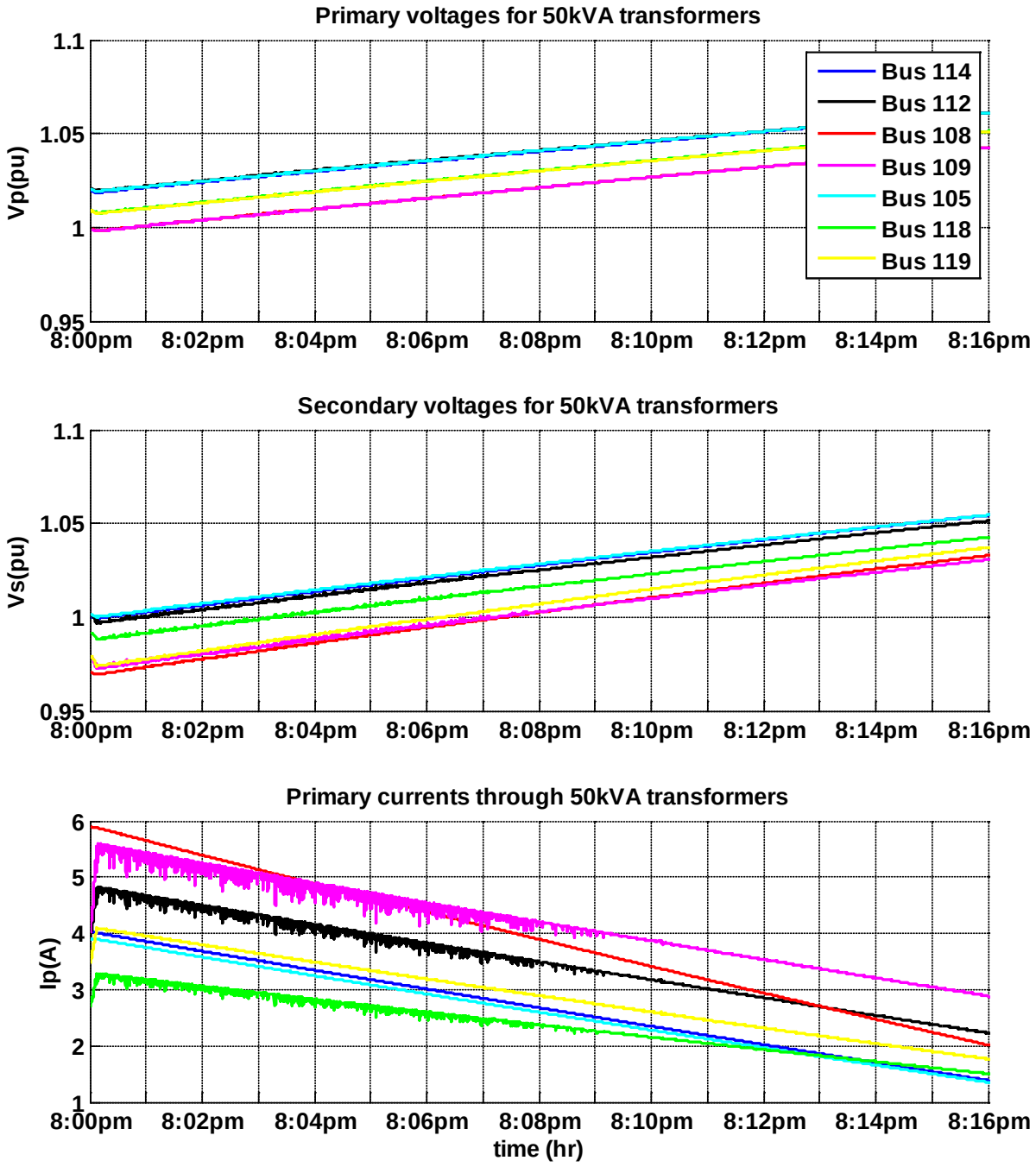

Figure 69 – Primary and secondary voltages and current at 50kVA transformers (8:00pm start)

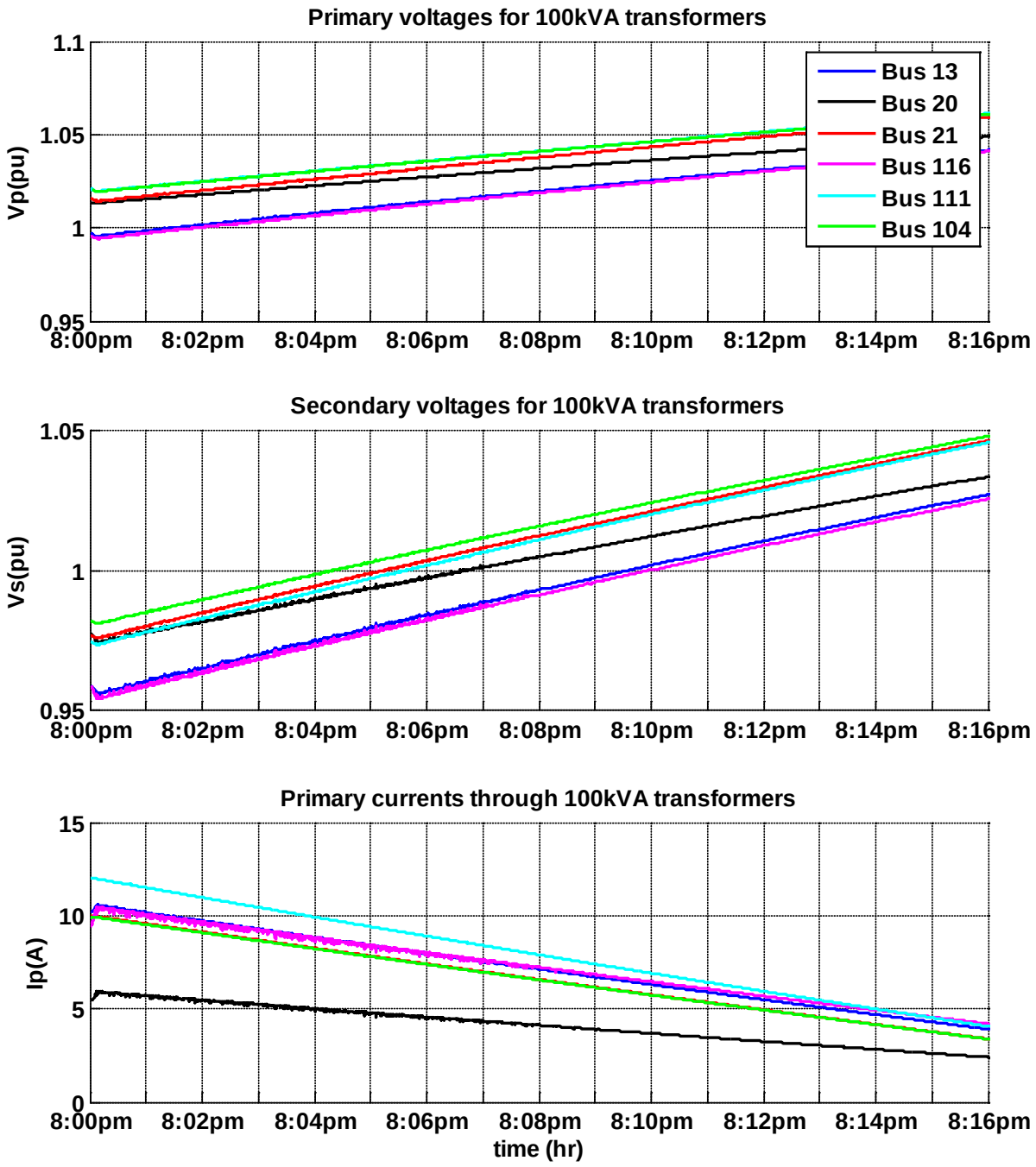

Figure 70 – Primary and secondary voltages and current at 100kVA transformers (8:00pm start)

3.8 *Online – Full system test – all customers have EV (15 minutes real time)*

This test covered a hypothetical scenario, where all transformers (excluding the three-phase loads on the first part of the system) had EV customers. The test was performed starting at both 12:00pm and 8:00pm. EV outputs were added at all (28) transformer secondaries. EV Set 1 (random distribution) defines the sizes and EVs are on for the entire 15 minute period. The details for EV size are given in *Table 8*, with the original 14 EV customers being shaded.

Table 8 – EV size for all potential customers (28)

	Transformer Parameters			Load and PV			EV Size
Bus #	XFMR kVA		Connection	Total Load		Total PV	Set 1
	Rated	Actual		kW	kVAR	kW	kW
10	50.00	70.00	A	55.00	9.00	5.92	9.80
11	50.00	35.00	C	28.00	4.00	4.60	6.60
13	100.00	88.00	A	69.00	12.00	9.80	3.30
15	50.00	41.00	AB	55.00	10.00	12.70	3.30
16	50.00	41.00		56.00	9.00	5.00	5.80
17	50.00	41.00	AB	55.00	9.00	6.00	5.80
20	100.00	82.00	AC	235.00	41.00		6.60
21	100.00	89.00	B	70.00	12.00	4.70	5.80
22	25.00	16.00	B	14.00	3.00	3.30	9.80
23	25.00	18.00	B	14.00	2.00		3.30
18	50.00	35.00	A	28.00	5.00	1.50	3.30
19	50.00	32.00	A	41.00	7.00	3.30	5.80
113	50.00	35.00	C	28.00	5.00	27.50	6.60
114	50.00	36.00	B	29.00	6.00	5.00	5.80
116	100.00	82.00	A	137.00	24.00	13.20	6.60
111	100.00	108.00	B	84.00	14.00	4.60	5.80
112	50.00	35.00	B	28.00	5.00	4.70	5.80
107	50.00	52.00	A	41.00	7.00	5.20	5.80
108	50.00	52.00	A	41.00	7.00	4.90	6.60
109	50.00	35.00	A	28.00	5.00	4.30	9.80
104	100.00	89.00	B	70.00	12.00	10.90	9.80
105	50.00	35.00	B	28.00	5.00	5.20	5.80
106	25.00	17.00	B	14.00	2.00		9.80
118A	50.00	41.00	AB	55.00	10.00	9.50	6.60
118B	50.00	46.00	BC	260.00	10.00	9.50	9.80
119	50.00	53.00	AB	42.00	7.00		6.60
120	25.00	24.00	C	19.00	3.00	5.06	9.80
121	25.00	24.00	C	19.00	3.00	5.40	5.80

3.8.1 Start at 12:00pm

Voltages for the entire circuit for uncontrolled charging are shown in *Figure 71*. Voltages for selected locations on each subsystem are shown in *Figure 72*. Transformer voltages and currents are shown in *Figure 73* through *Figure 76*. Around noon time, PV production was strong. Due to reduction in load based on the given profile, voltage started to increase despite the presence of EV charging. The voltages showed about a 2% to 2.5% increase from the no EV condition. In a few locations, the voltage had passed 1.05 pu.

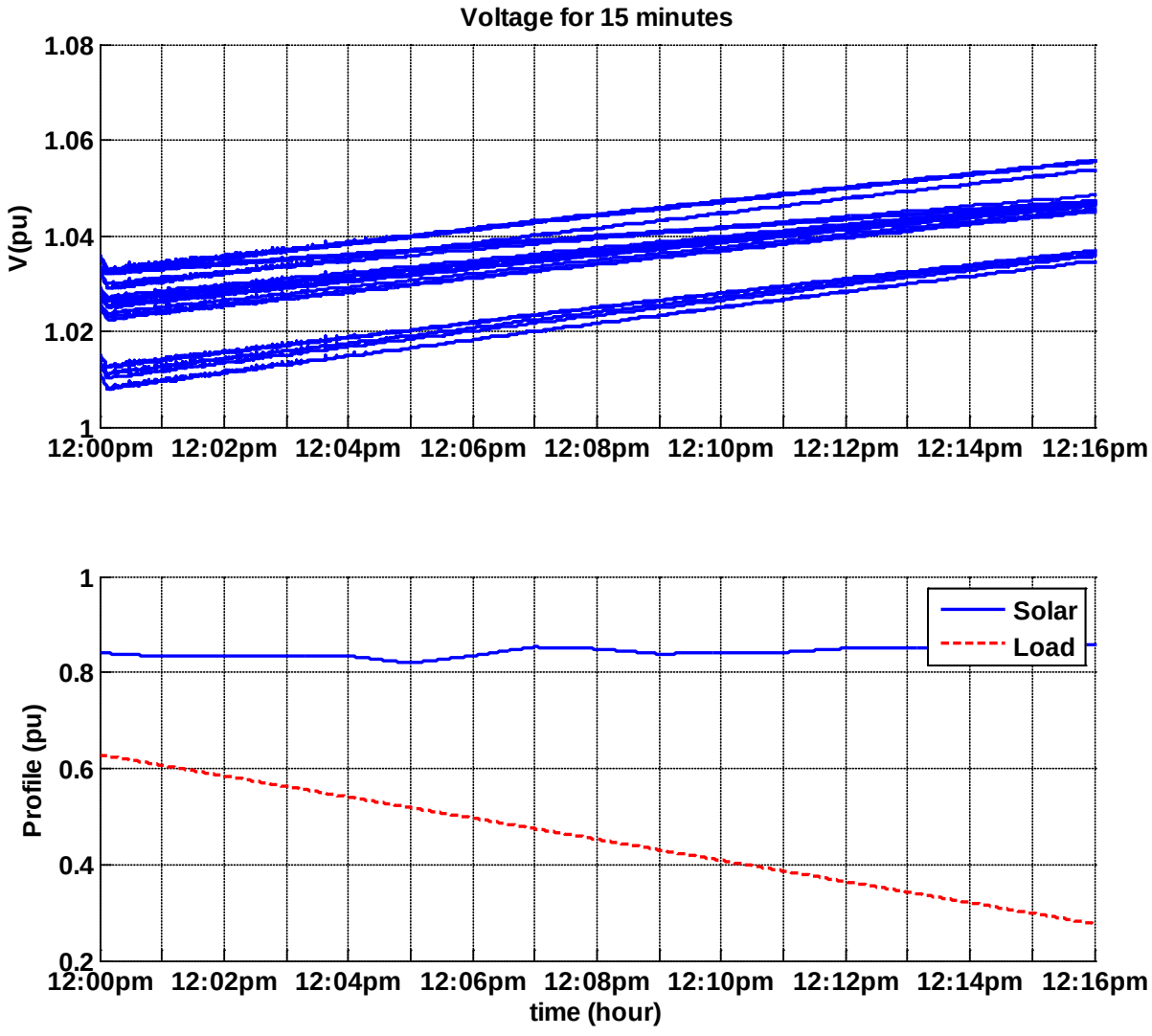

Figure 71 – Voltage at all circuit locations for varying load and PV profile (12:00pm start)

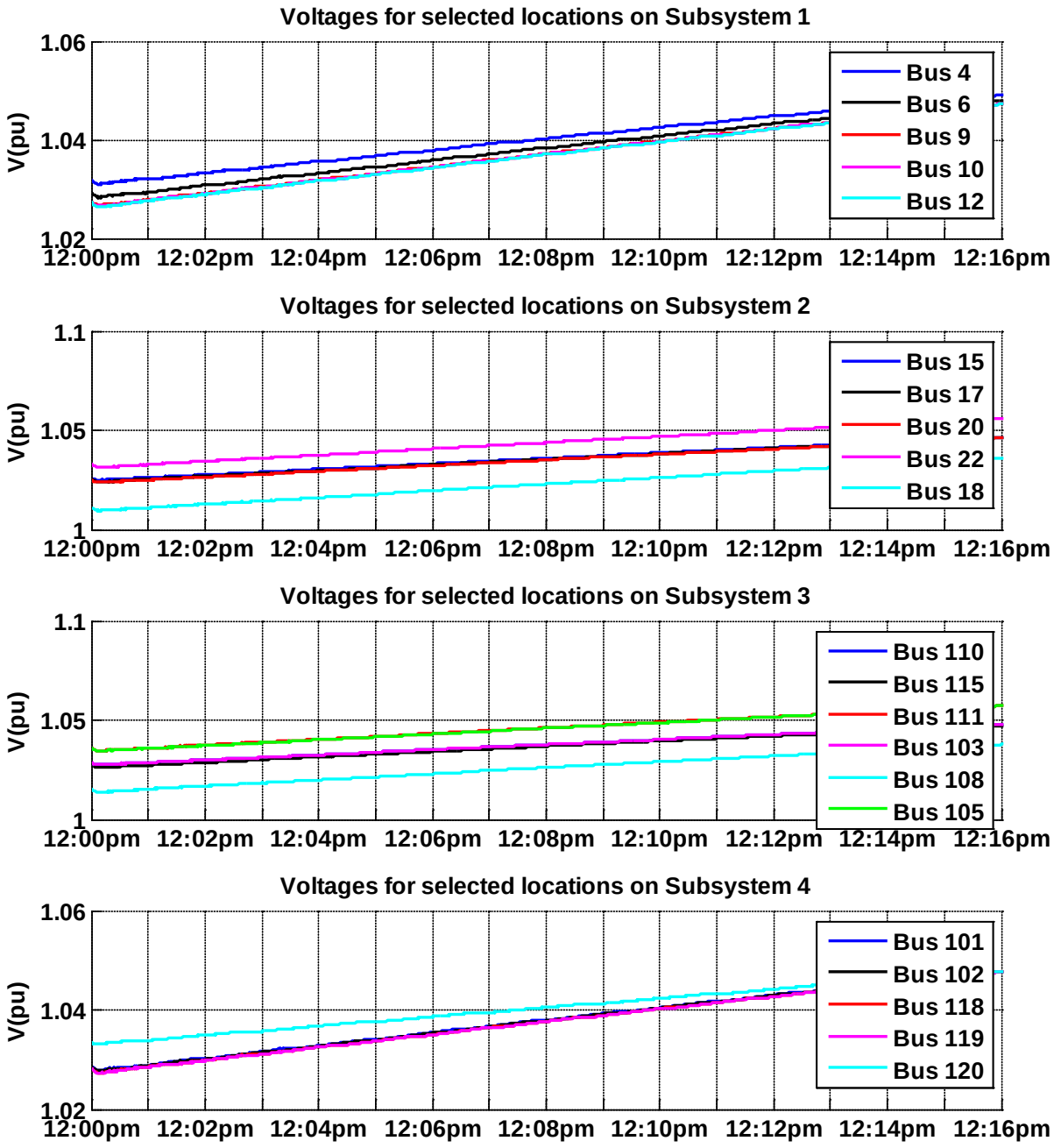

Figure 72 – Voltage at selected circuit locations for varying load and PV profile (12:00pm start)

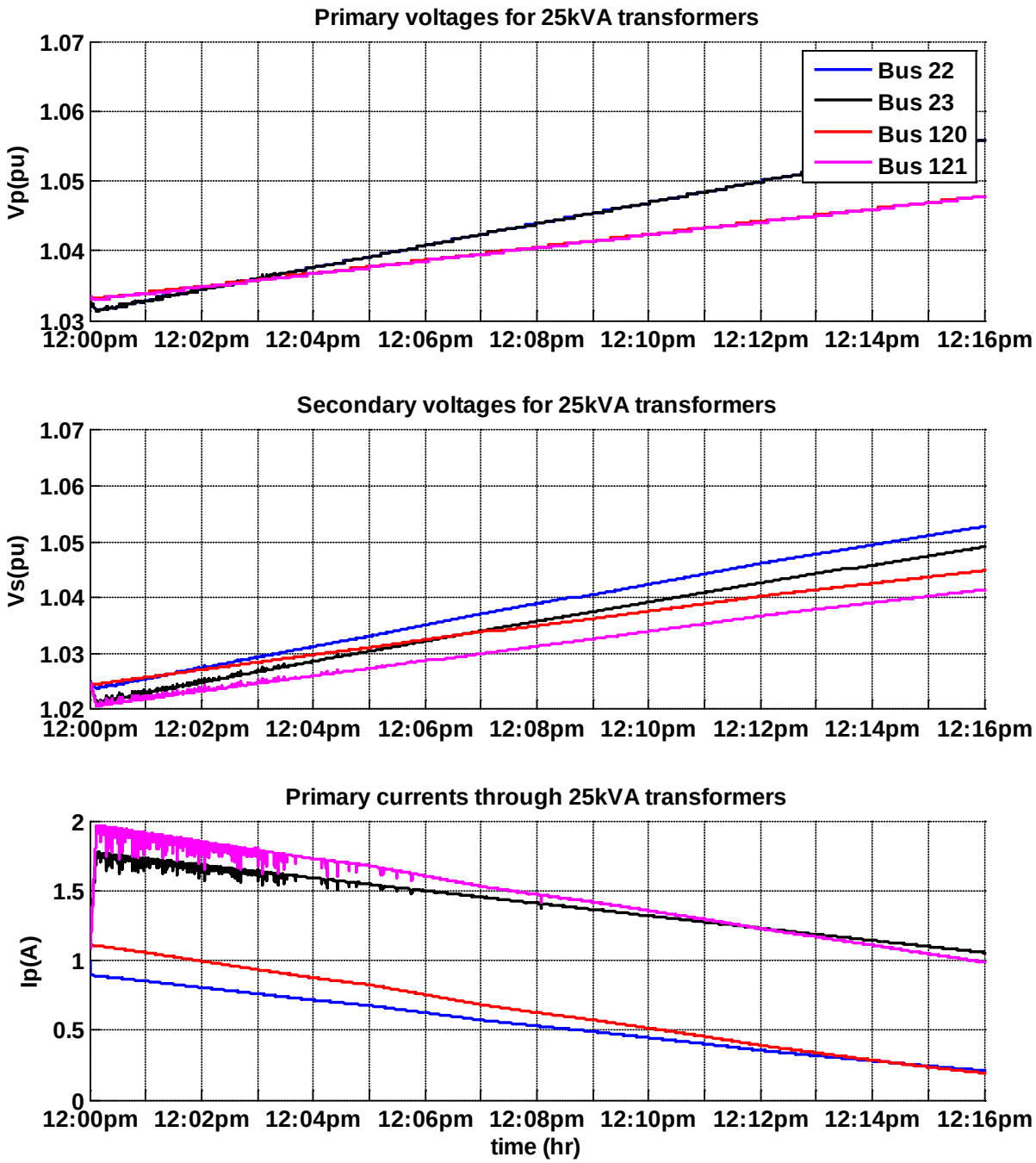

Figure 73 – Primary and secondary voltages and current at 25kVA transformers (12:00pm start)

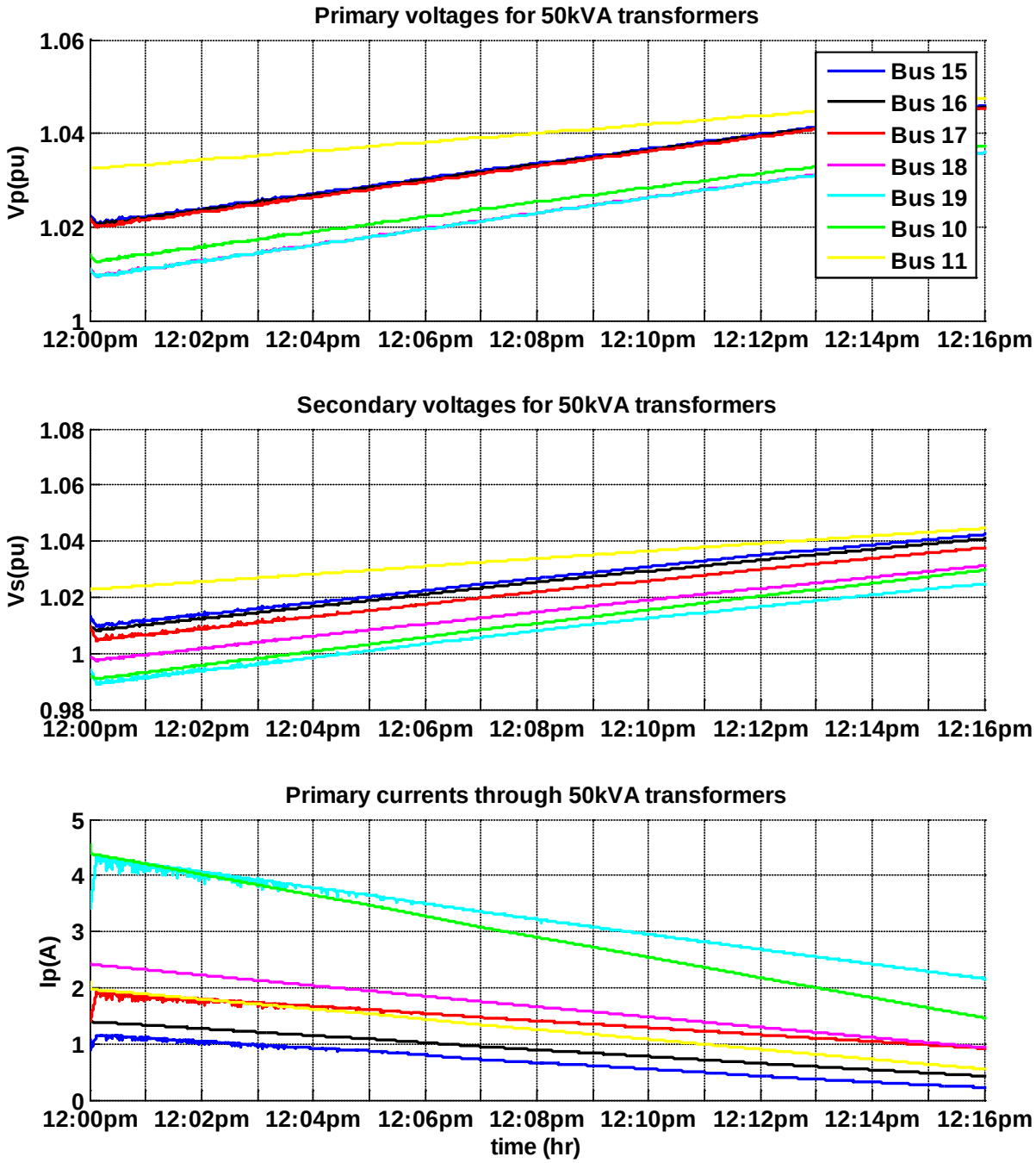

Figure 74 – Primary and secondary voltages and current at 50kVA transformers (12:00pm start)

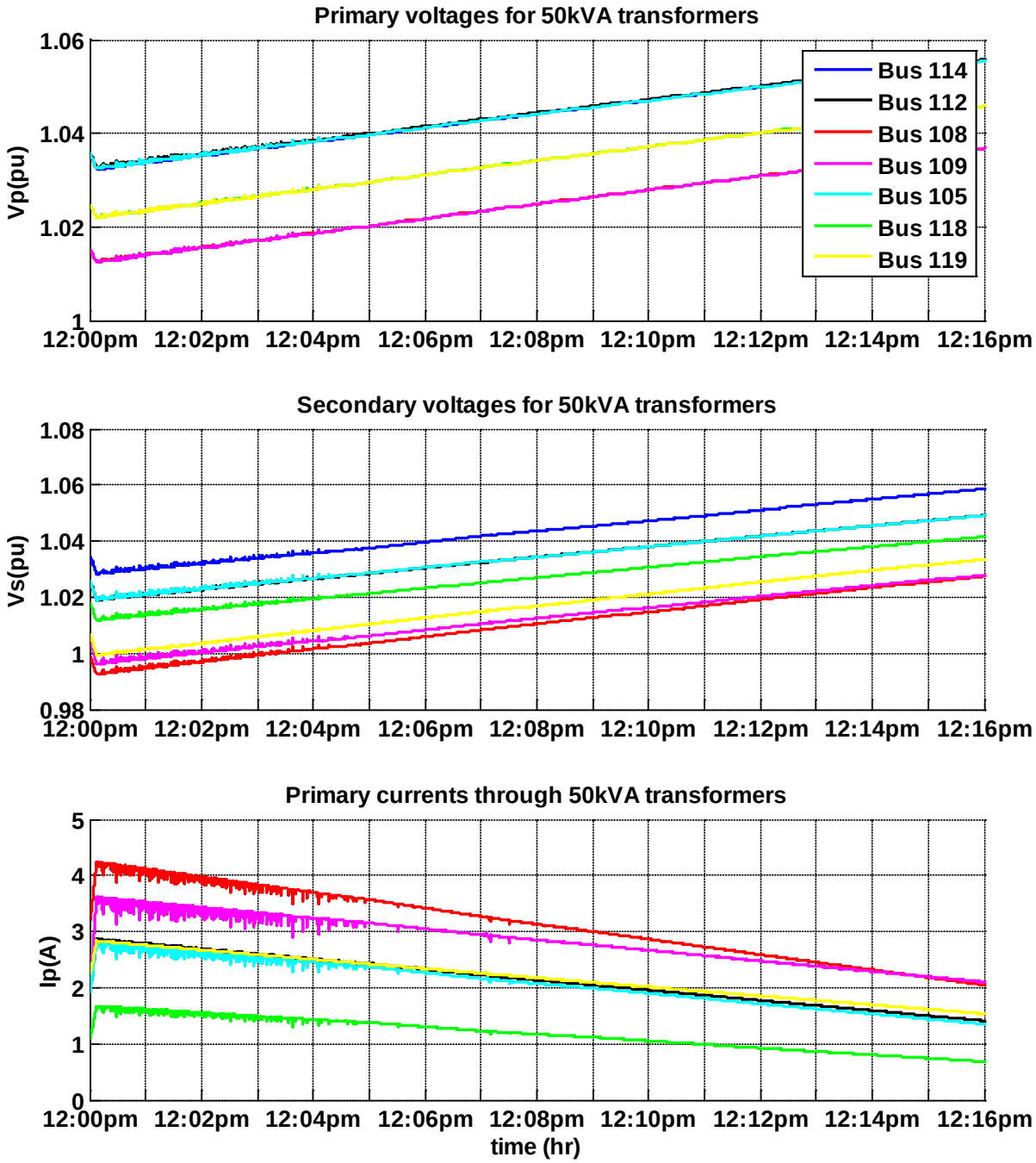

Figure 75 – Primary and secondary voltages and current at 50kVA transformers (12:00pm start)

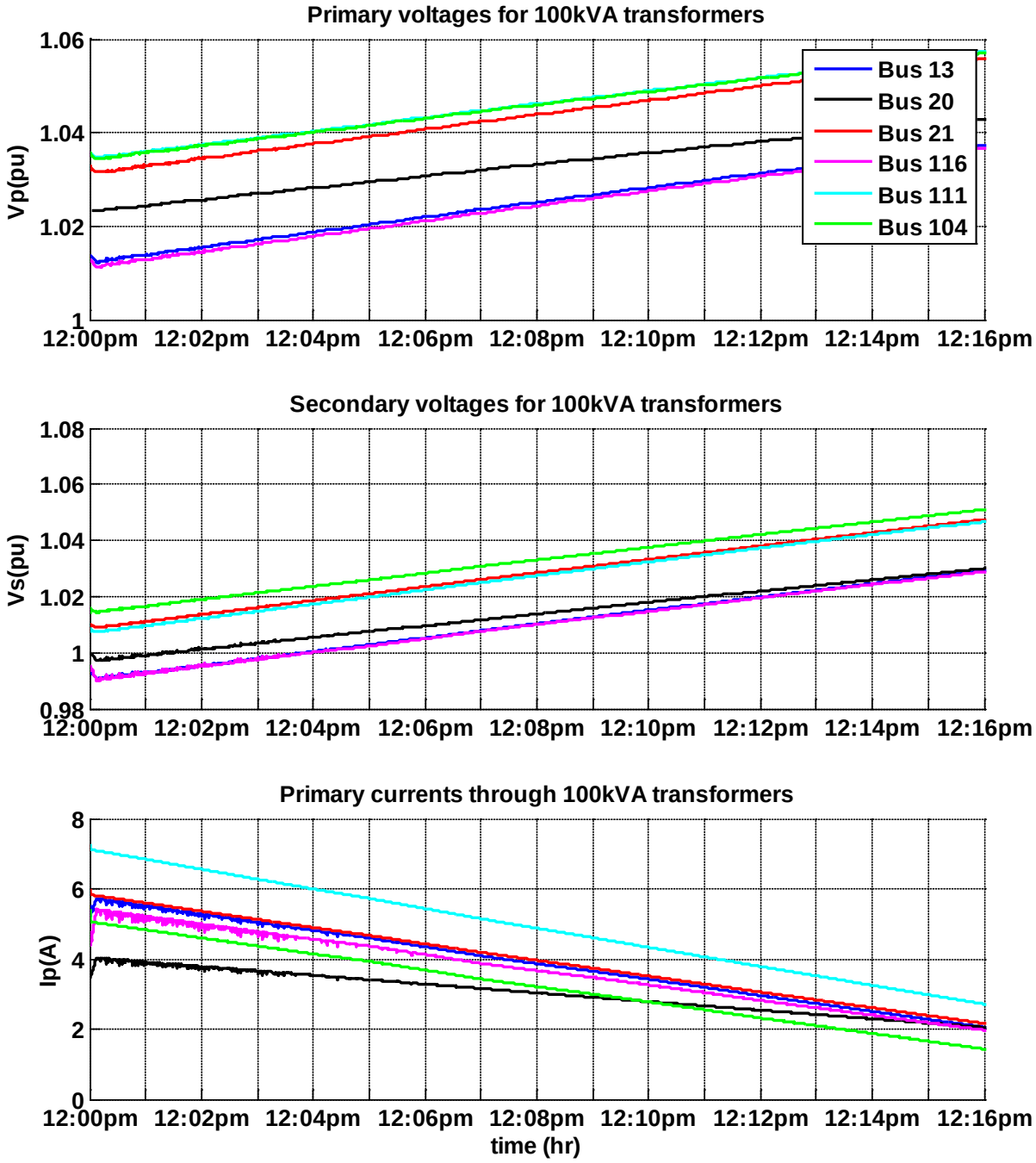

Figure 76 – Primary and secondary voltages and current at 100kVA transformers (12:00pm start)

3.8.2 Start at 8:00pm

Voltages for the entire circuit for uncontrolled charging are shown in *Figure 77*. Voltages for selected locations on each subsystem are shown in *Figure 78*. Transformer voltages and currents are shown in *Figure 79* through *Figure 82*.

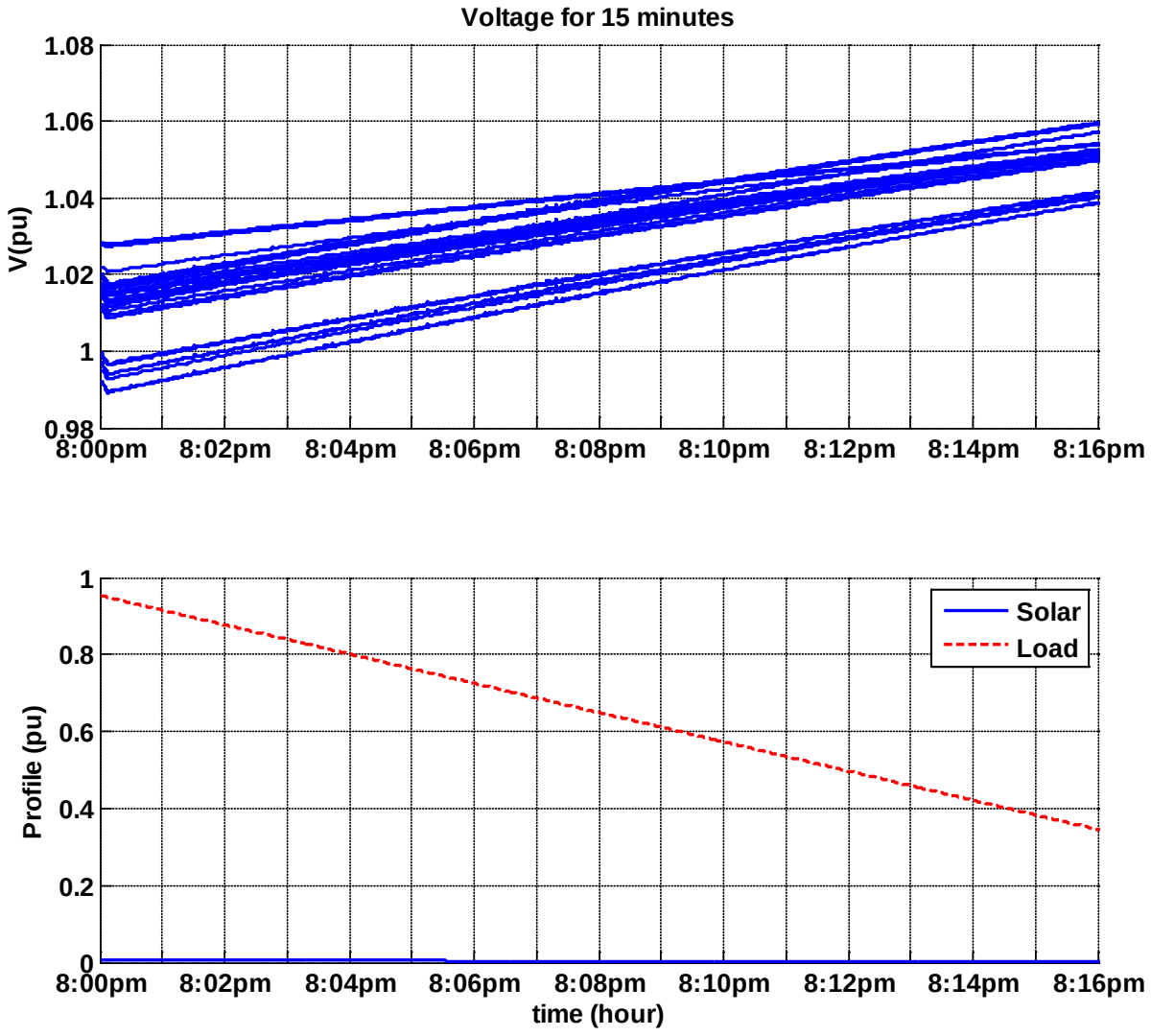

Figure 77 – Voltage at all circuit locations for varying load and PV profile (8:00pm start)

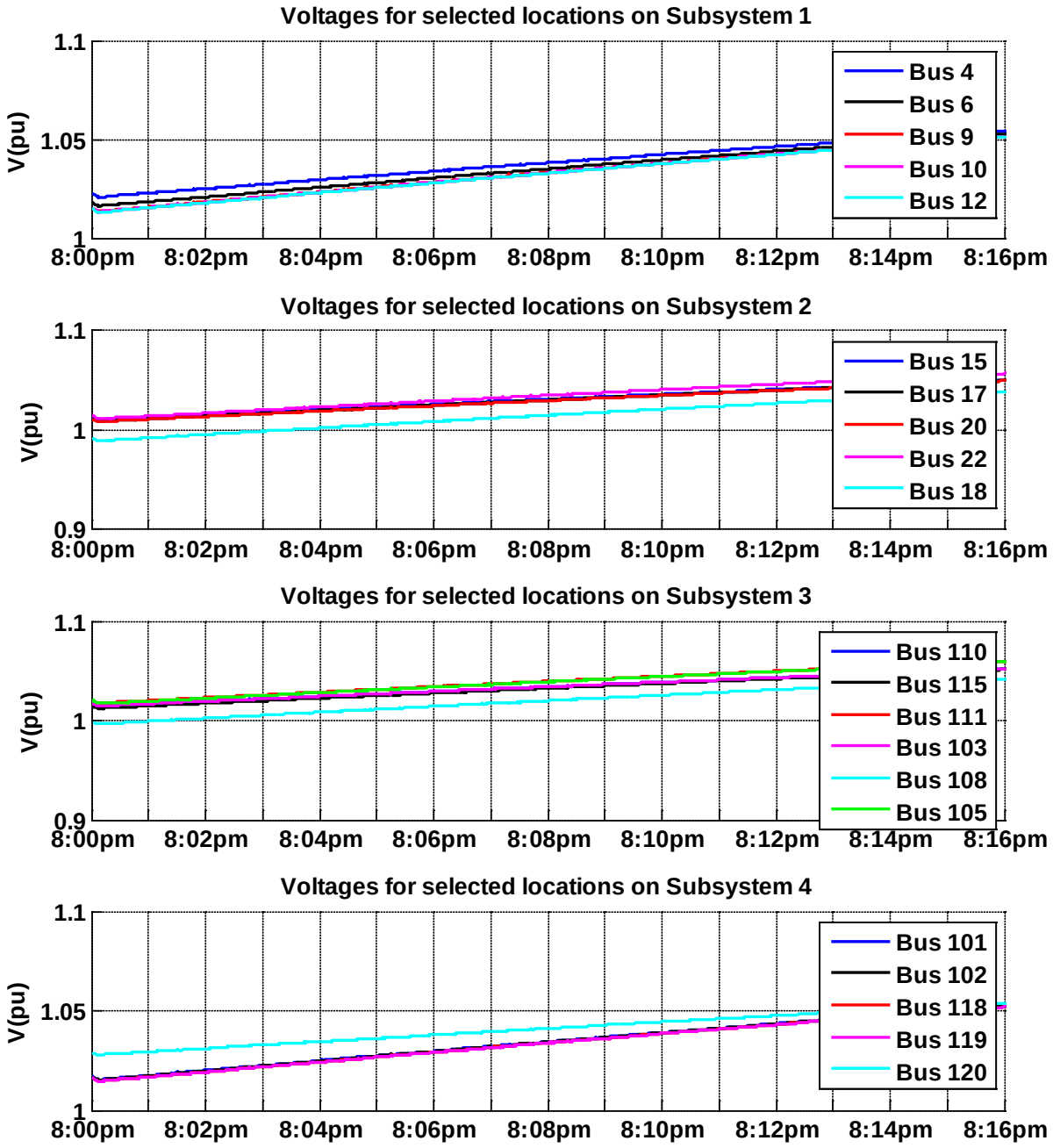

Figure 78 – Voltage at selected circuit locations for varying load and PV profile (8:00pm start)

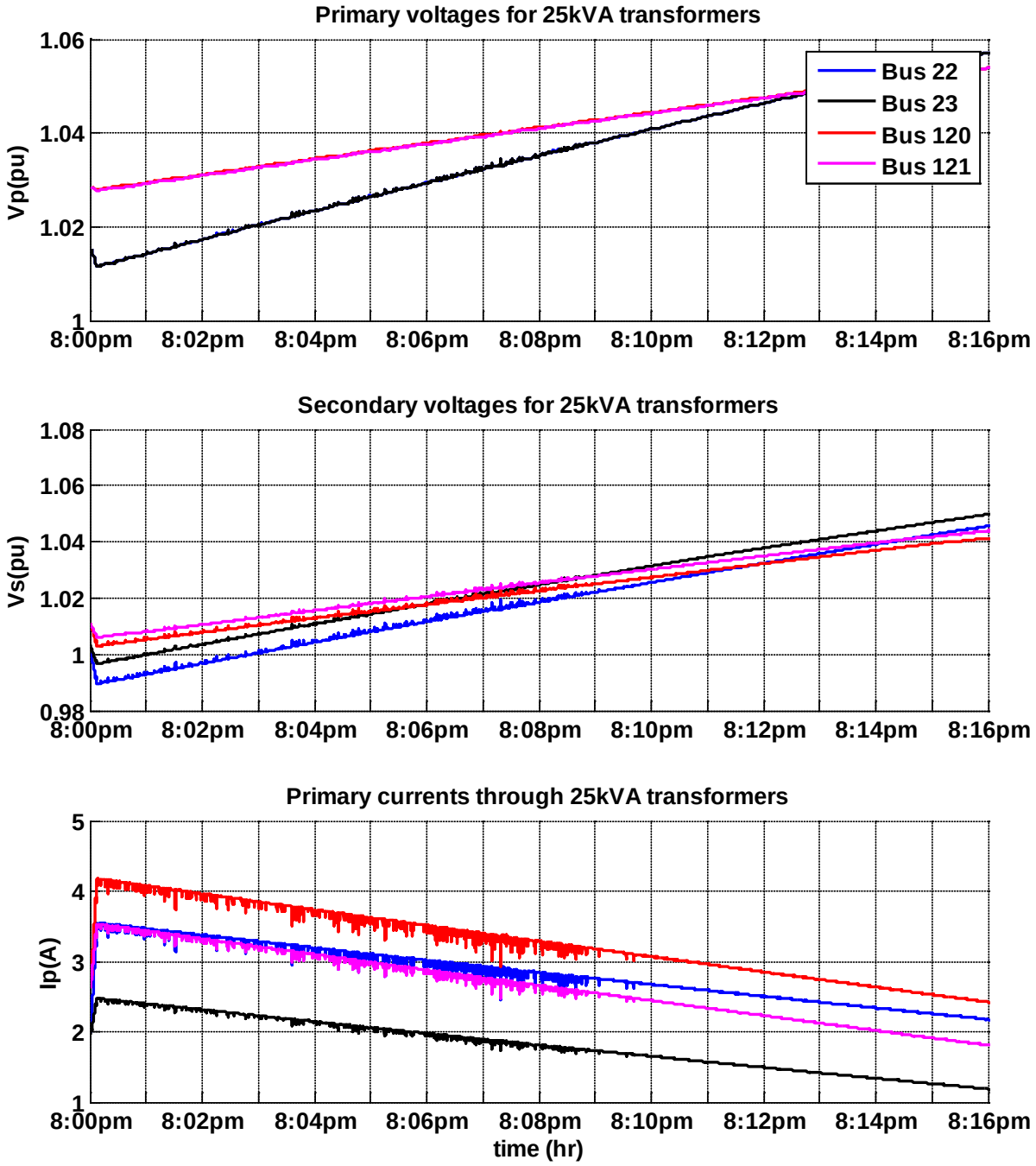

Figure 79 – Primary and secondary voltages and current at 25kVA transformers (8:00pm start)

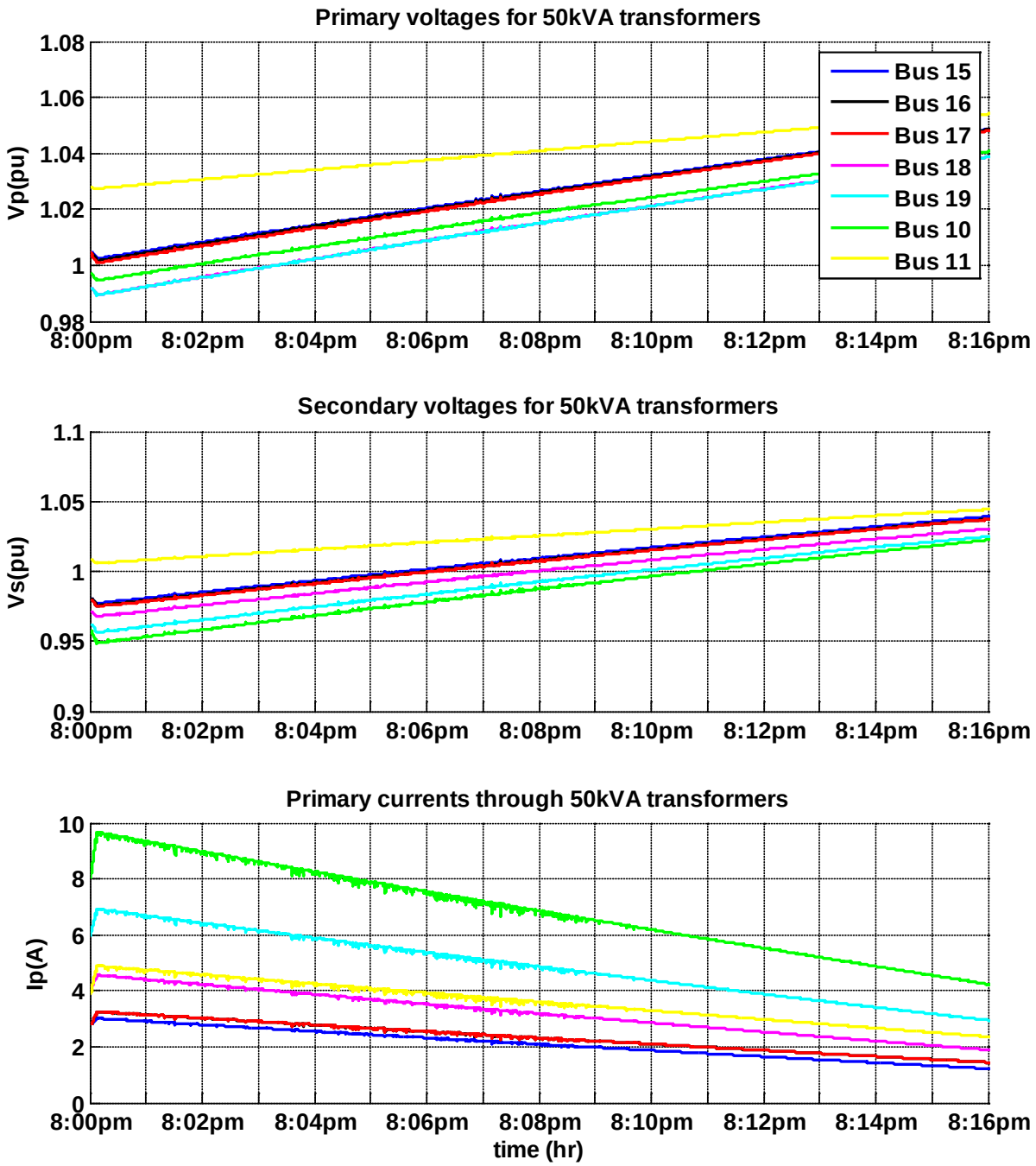

Figure 80 – Primary and secondary voltages and current at 50kVA transformers (8:00pm start)

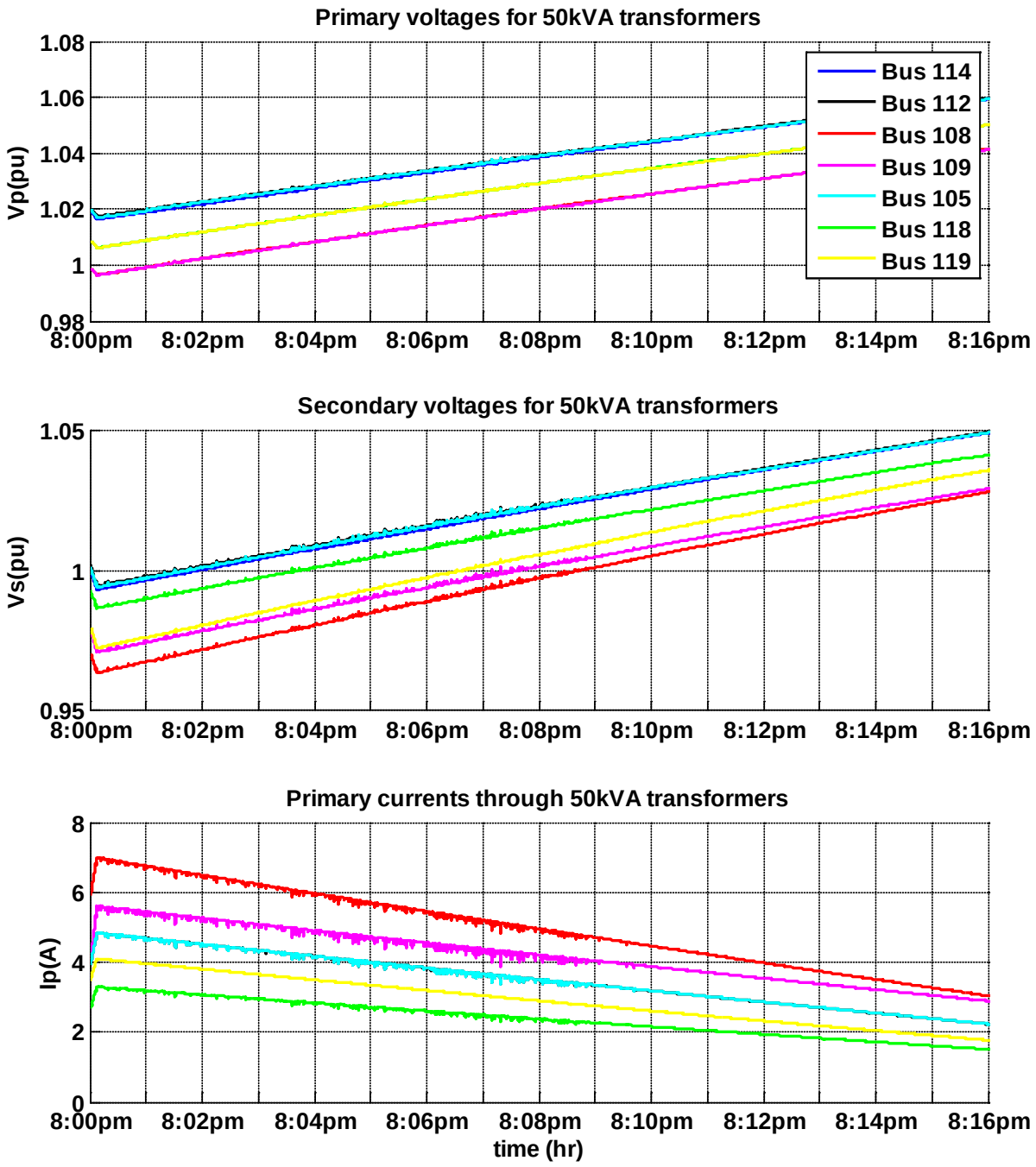

Figure 81 – Primary and secondary voltages and current at 50kVA transformers (8:00pm start)

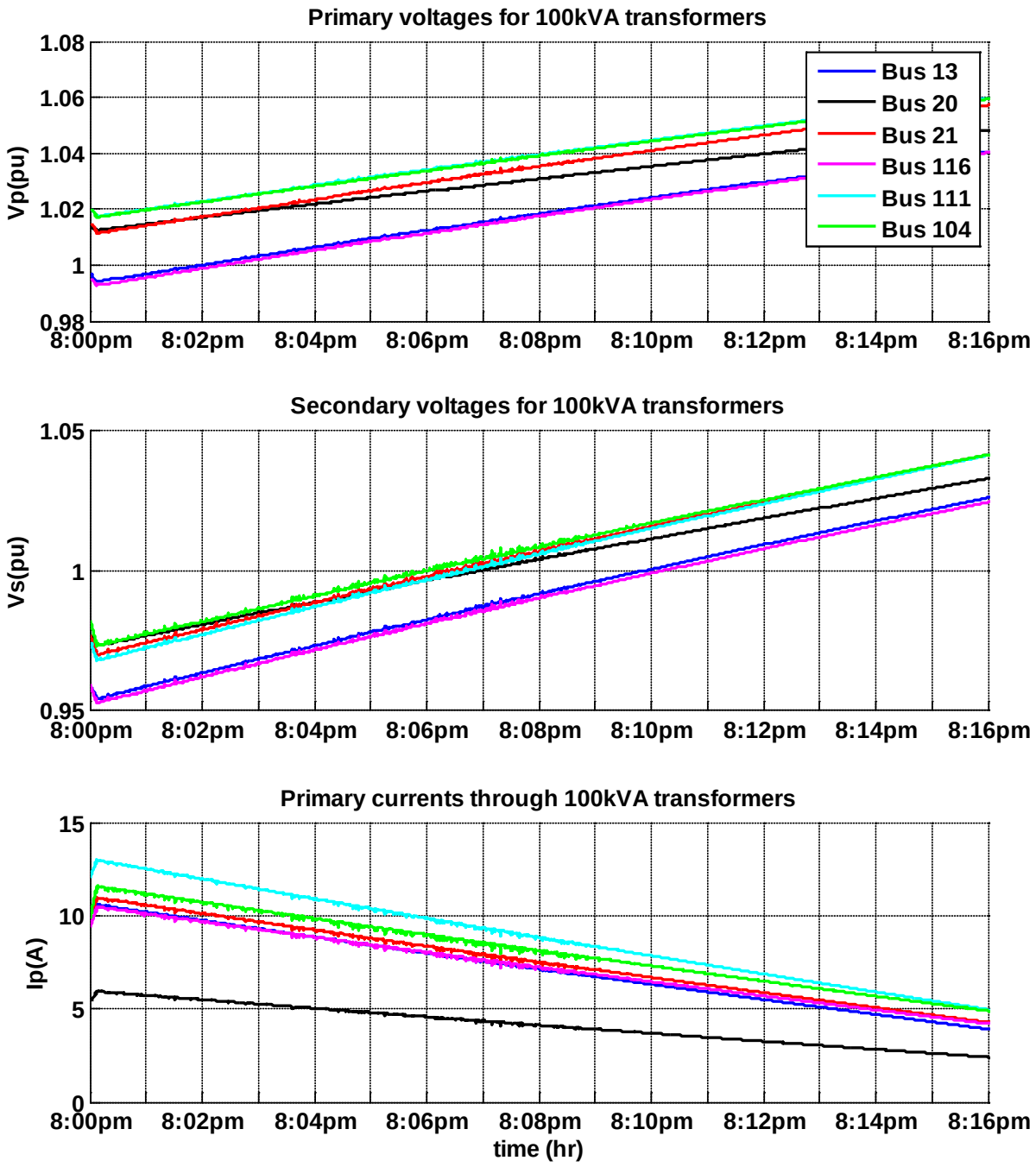

Figure 82 – Primary and secondary voltages and current at 100kVA transformers (8:00pm start)

3.9 *Online – Single EV on circuit (24 hours accelerated time)*

These tests involved the connection of one EV customer to the circuit, with both scaled loads and the PV generation with output scaled to the full 24-hour profile. Three locations were selected for the connection of the EV customer, representing the location of measurement of the voltage waveform to send to the grid simulator, and a range of secondary circuit transformer ratings:

- Bus 119 – Location of voltage waveform measurement, EV size was 6.6kW
- Bus 116 – 100kVA transformer, EV size was 6.6kW
- Bus 109 – 50kVA transformer, EV size was 9.8kW

The EV was configured to charge for the entire period between 4:00pm to 4:00am the next morning.

3.9.1 EV at Bus 119

Voltages for the entire circuit and for the transformer are shown in *Figure 83*. It was observed that EV charging had a large effect on primary transformer current flow, but only a minor effect on the primary transformer voltage. Based on the load profile and added demand of the EV charges, the secondary voltage in early evening (6 to 8 pm) could go below 0.98 pu as the acceptable range.

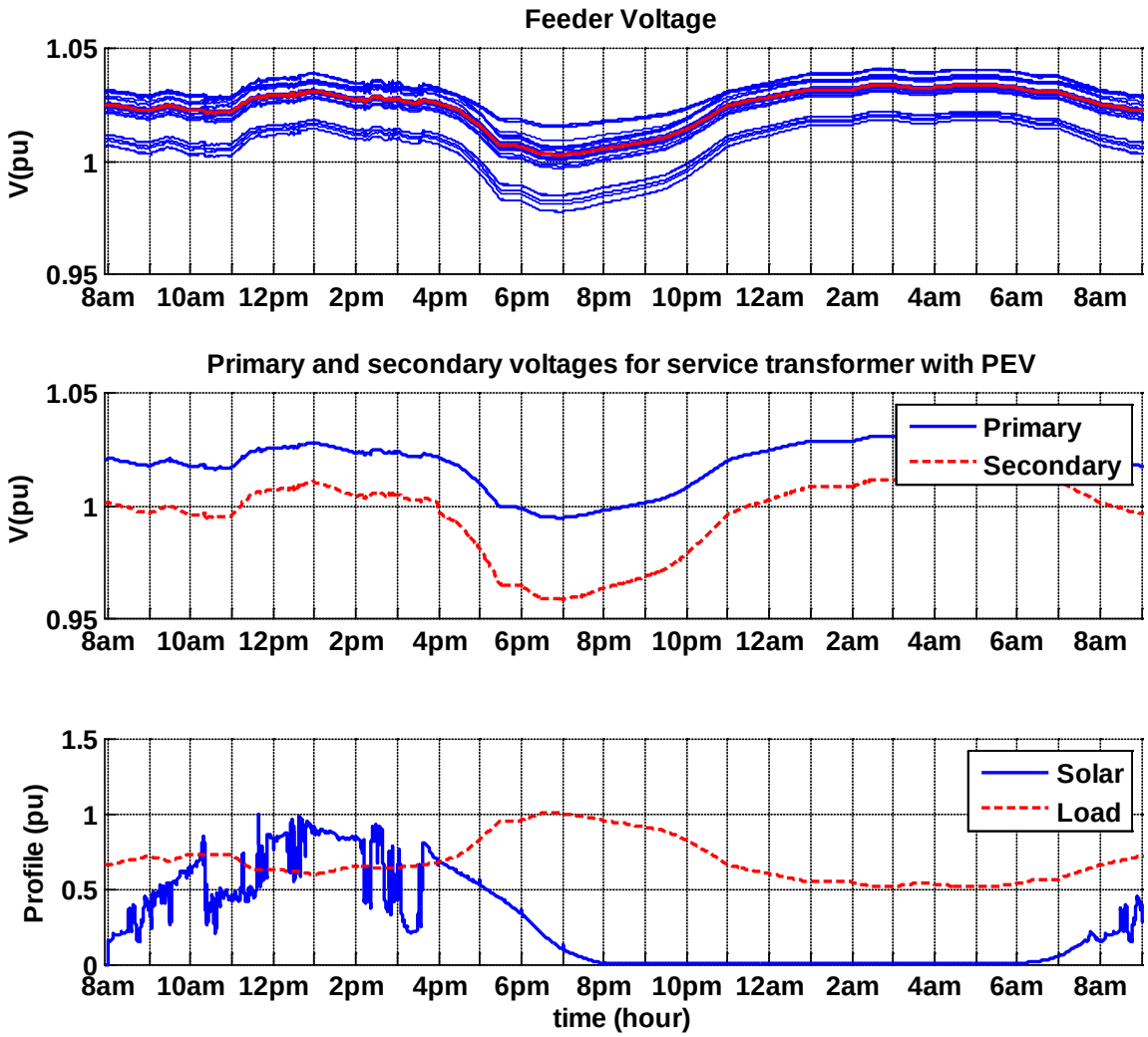

Figure 83 – Circuit voltage and voltages for transformer at Bus 119

3.9.2 EV at Bus 116

Voltages for the entire circuit and transformer are shown in *Figure 84*. It was observed that EV charging had a large effect on primary transformer current flow and the secondary transformer voltage. EV charging had less effect on the primary circuit voltages.

The voltage drop due to EV charging was about 2%.

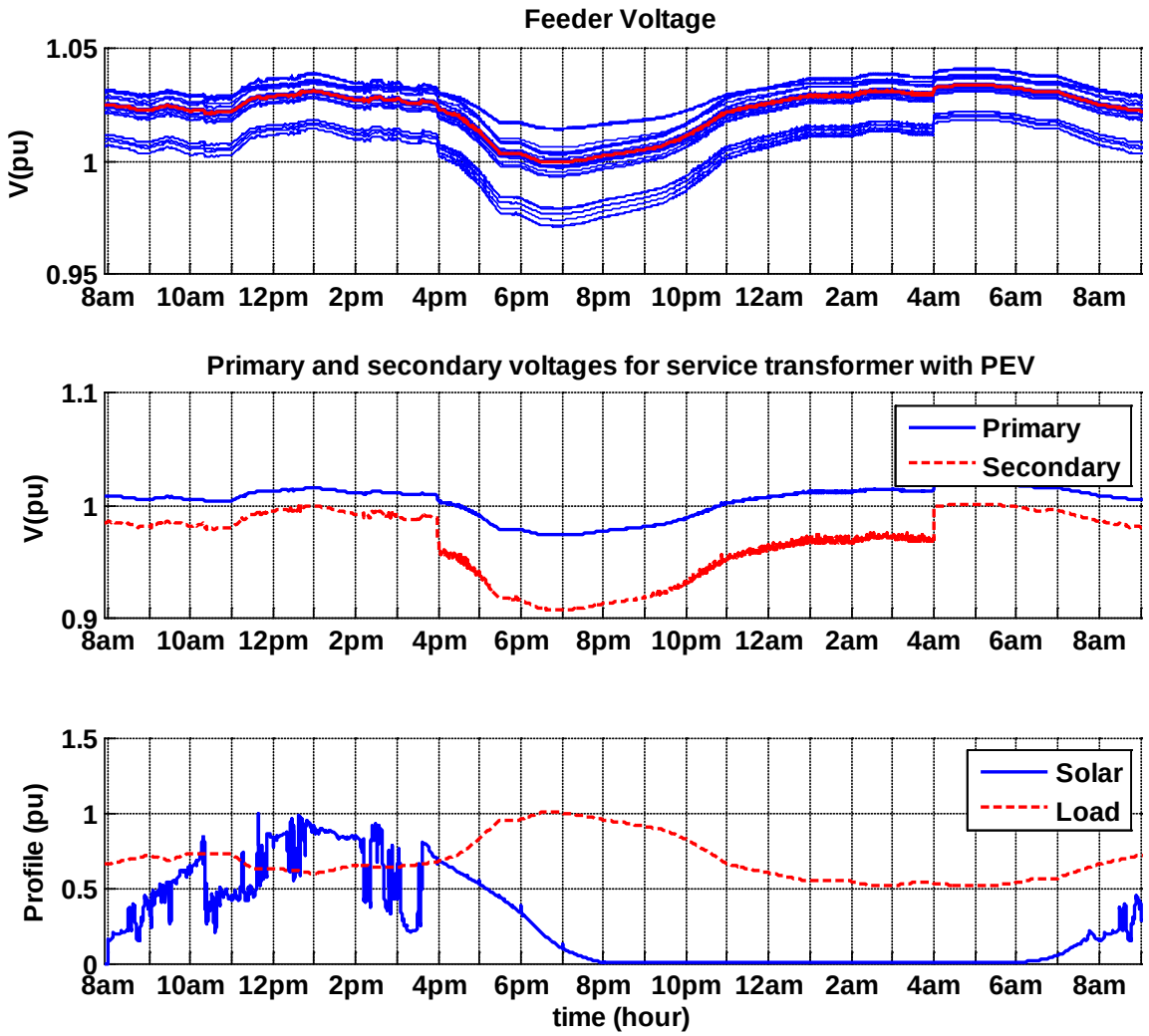

Figure 84 – Circuit voltage and voltages for transformer at Bus 116

3.9.3 EV at Bus 109

Voltages for the entire circuit and for the transformer are shown in *Figure 85*. It was observed that EV charging had a large effect on both primary transformer current flow and the secondary transformer voltage. EV charging had less effect on the primary circuit voltage.

The voltage drop due to EV charging was about 5%. Voltage had reached a low level about 0.9 pu on secondary circuits.

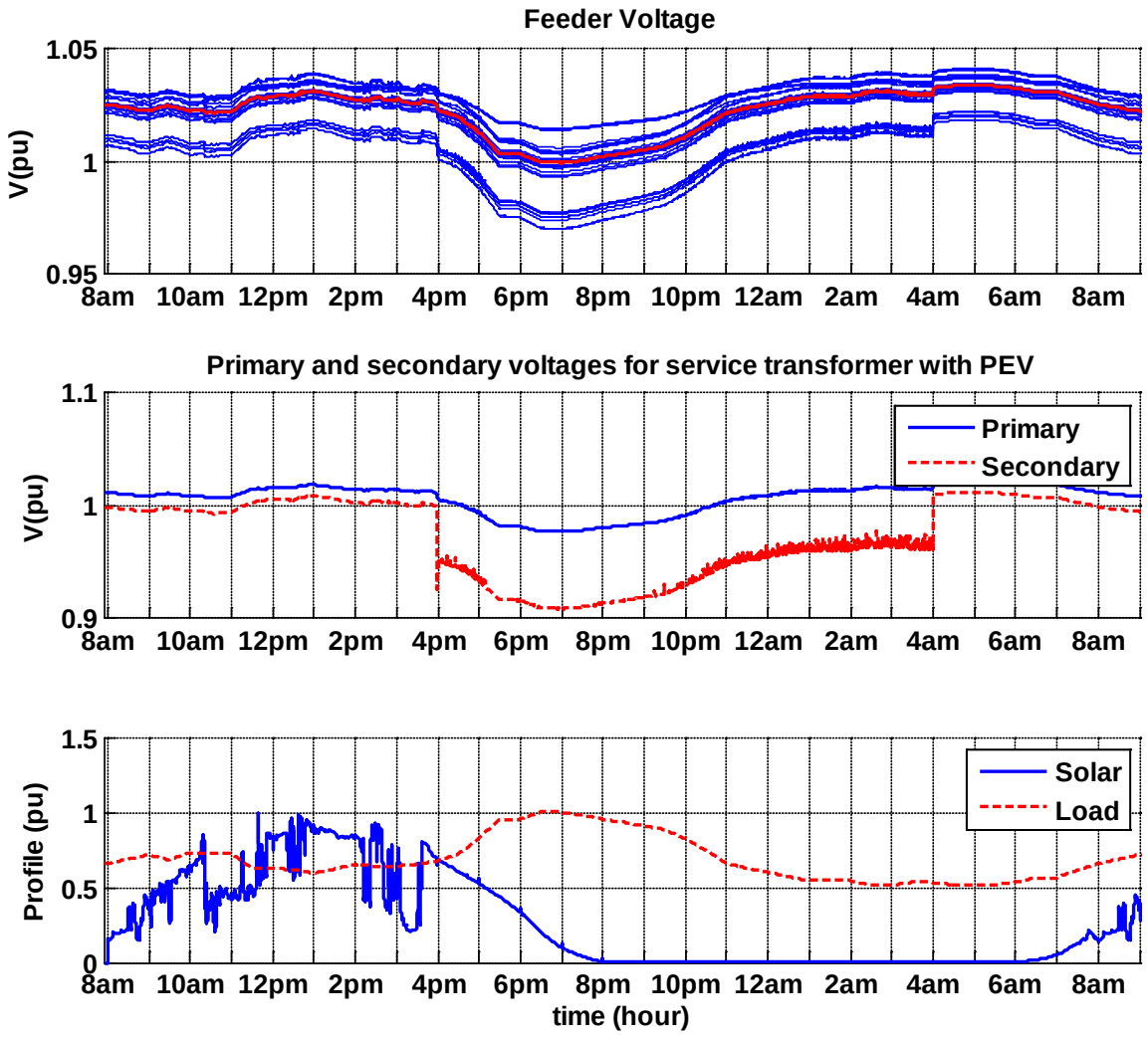

Figure 85 – Circuit voltage and voltages for transformer at Bus 109

3.10 *Online - Full system test – existing number of customers*

In this test, EV outputs were added at fourteen (14) existing customer locations. EV sizes and charging times were randomly assigned according to the following:

- EV Set 1: Random distribution of 3.3kW, 5.8kW, 6.6kW, 9.8kW EV sizes
- EV Set 2: 4x 3.5kV, 8x 6.8kV, 2x 9.8kV
- Always on: EV was charging from 16:00 (4:00pm) through to 4:00 (4:00am) the next morning
- Uncontrolled Charging: 16:00 – 18:00 starting times, 22:00 – 4:00 end times

The period of time defined as uncontrolled charging was earlier in the day than the controlled charging time. Since base load was larger during the uncontrolled charging period, it was judged to have a larger effect on the system. The details for both EV size sets and uncontrolled charging times are given in ***Table 9***.

Table 9 – EV size sets and uncontrolled charging times for all existing customers (14)

	Transformer Parameters			Load and PV			EV Size		EV Charging Time	
Bus #	XFMR kVA		Connection	Total Load		Total PV	Set 1	Set 2	Uncontrolled Charging	
	Rated	Actual		kW	kVAR	kW	kW	kW	Start	End
13	100	88	A	69	12	9.8	3.3	3.5	16:30	22:30
15	50	41	AB	55	10	12.7	3.3	6.8	16:00	00:30
17	50	41	AB	55	9	6.0	5.8	3.5	16:30	23:30
20	100	82	AC	235	41		6.6	6.8	18:00	01:00
23	25	18	B	14	2		3.3	6.8	17:00	22:30
19	50	32	A	41	7	3.3	5.8	9.8	16:30	23:30
116	100	82	A	137	24	13.2	6.6	3.5	17:30	23:30
112	50	35	B	28	5	4.7	5.8	6.8	17:30	02:30
109	50	35	A	28	5	4.3	9.8	6.8	17:30	22:30
106	25	17	B	14	2		9.8	9.8	17:00	00:30
118A	50	41	AB	55	10	9.5	6.6	6.8	18:00	01:30
118B	50	46	BC	260	10	9.5	9.8	6.8	16:30	02:00
119	50	53	AB	42	7		6.6	3.5	17:30	04:00
121	25	24	C	19	3	5.4	5.8	6.8	16:00	02:30

3.10.1 EV Profile Set 1, EV Always On

Voltages for the entire circuit are shown in *Figure 86*. Voltages for selected locations on each subsystem are shown in *Figure 87*. Transformer voltages and currents are shown in *Figure 88* through *Figure 91*. It was observed that EV charging had a large effect on primary transformer current flow, but only a minor effect on the secondary transformer voltage. EV charging had no significant effect on the circuit voltage.

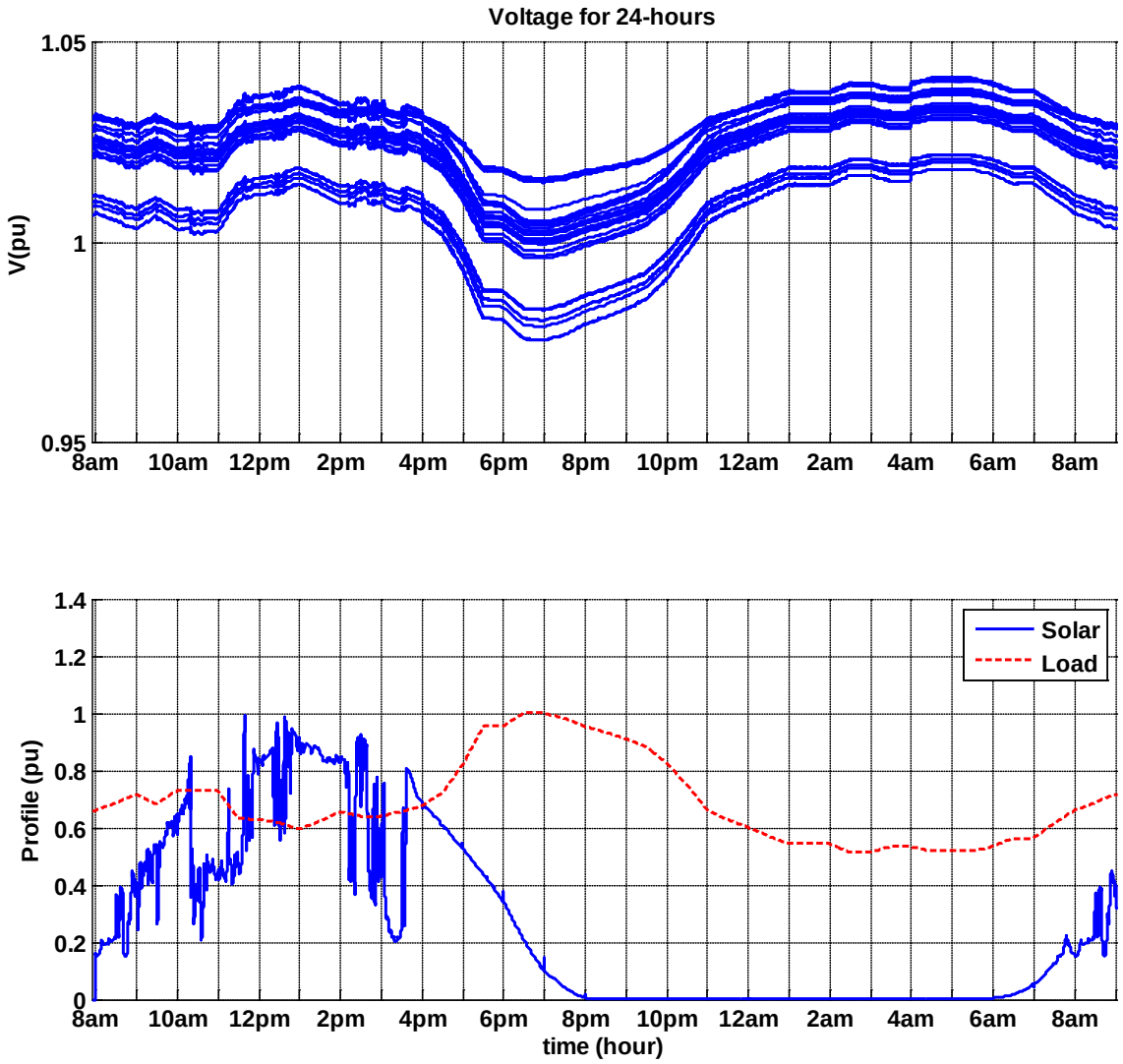

Figure 86 – Voltage at all circuit locations for varying load and PV profile (EV Set 1, Always on)

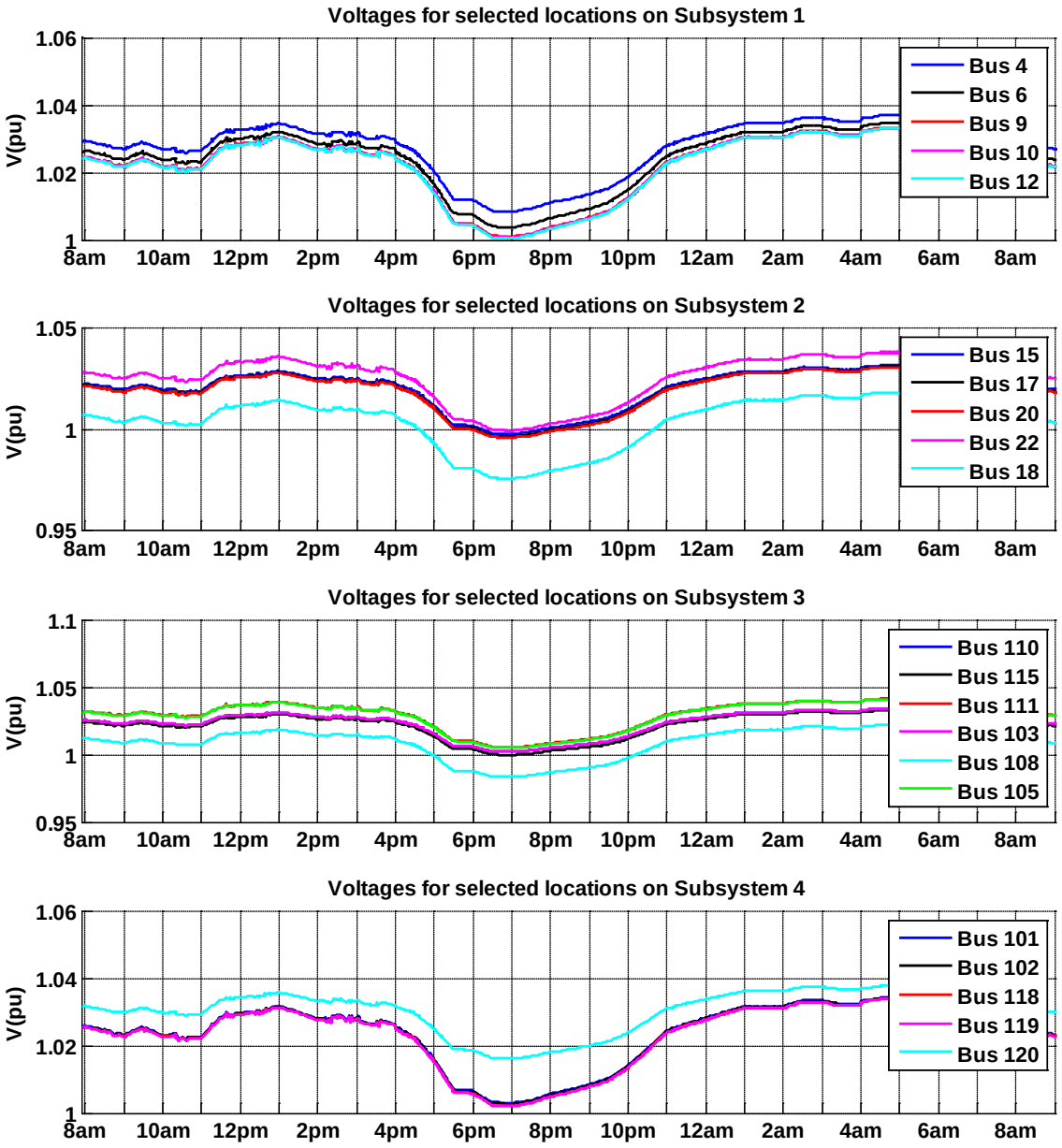

Figure 87 – Voltage at selected circuit locations for varying load and PV profile (EV Set 1, Always on)

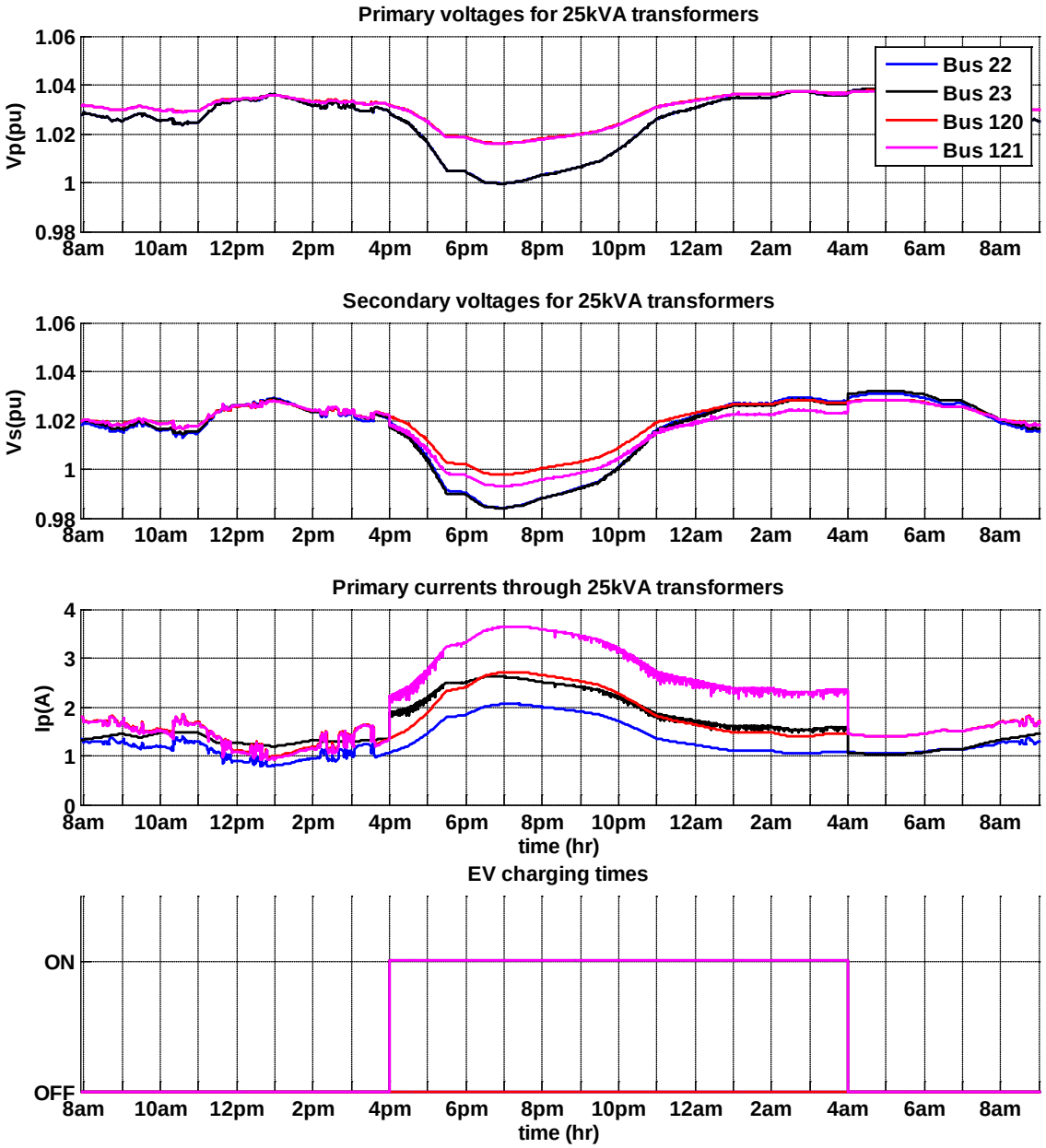

Figure 88 – Primary and secondary voltages and current at 25kVA transformers (EV Set 1, Always on)

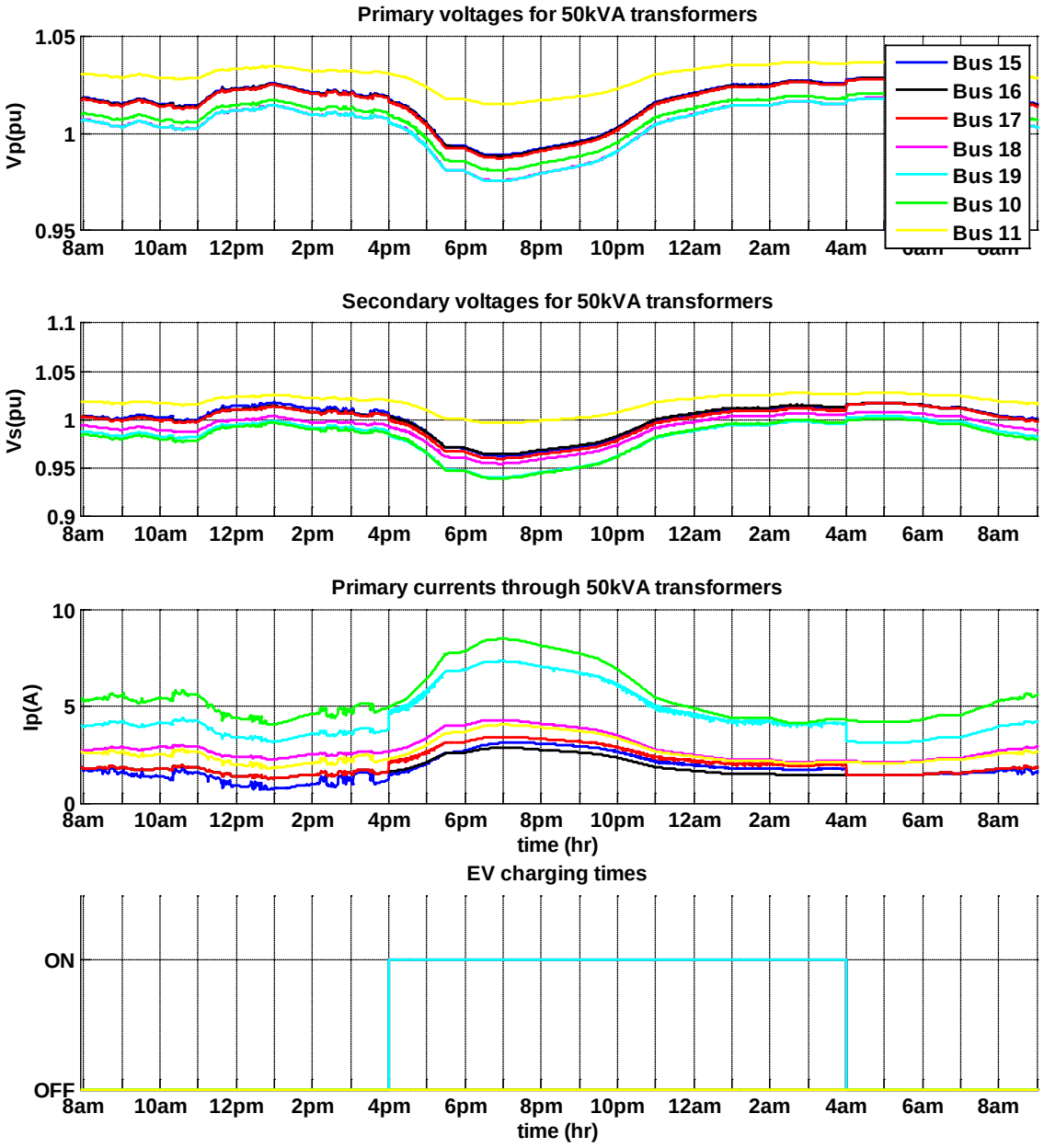

Figure 89 – Primary and secondary voltages and current at 50kVA transformers (EV Set 1, Always on)

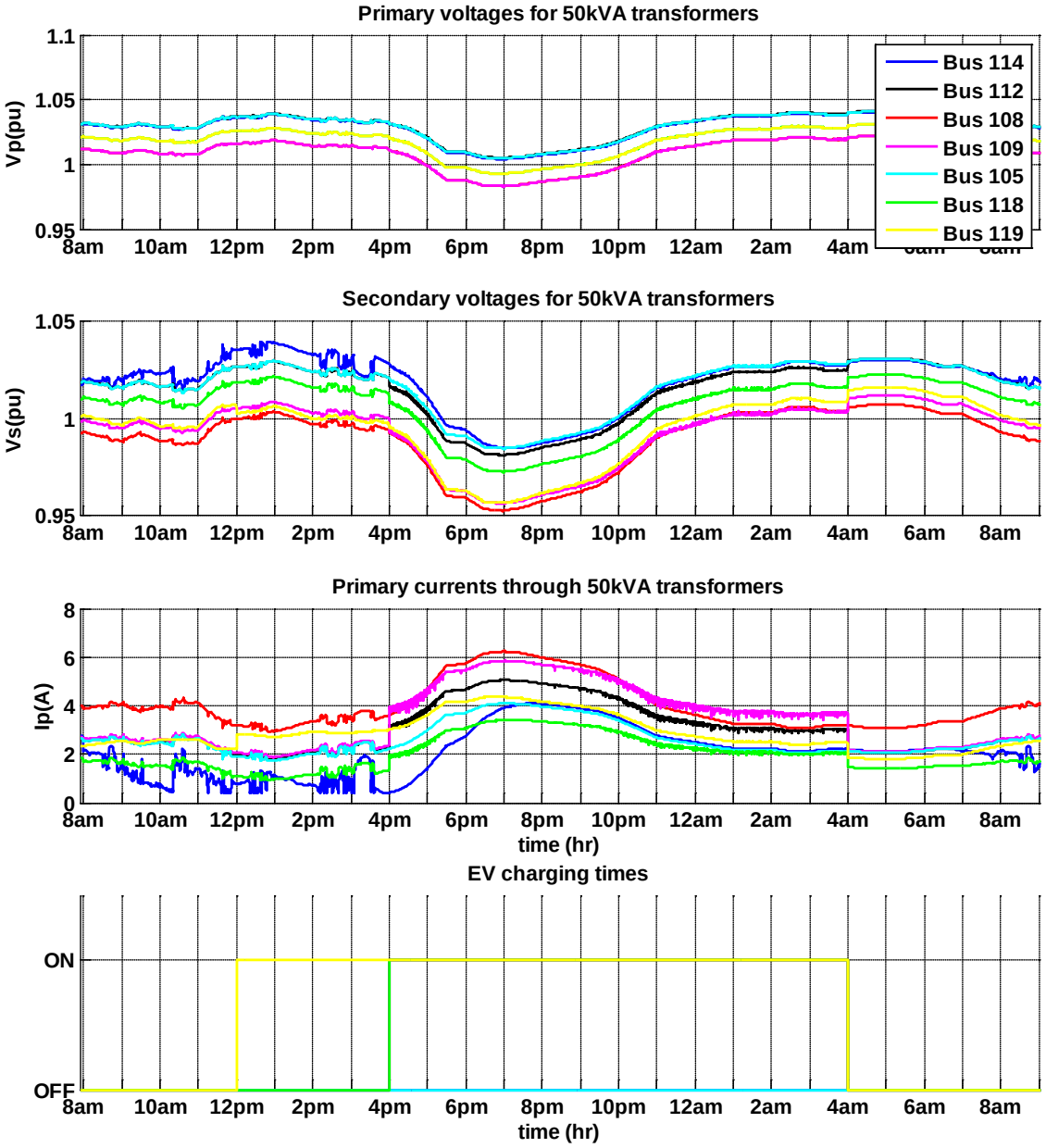

Figure 90 – Primary and secondary voltages and current at 50kVA transformers (EV Set 1, Always on)

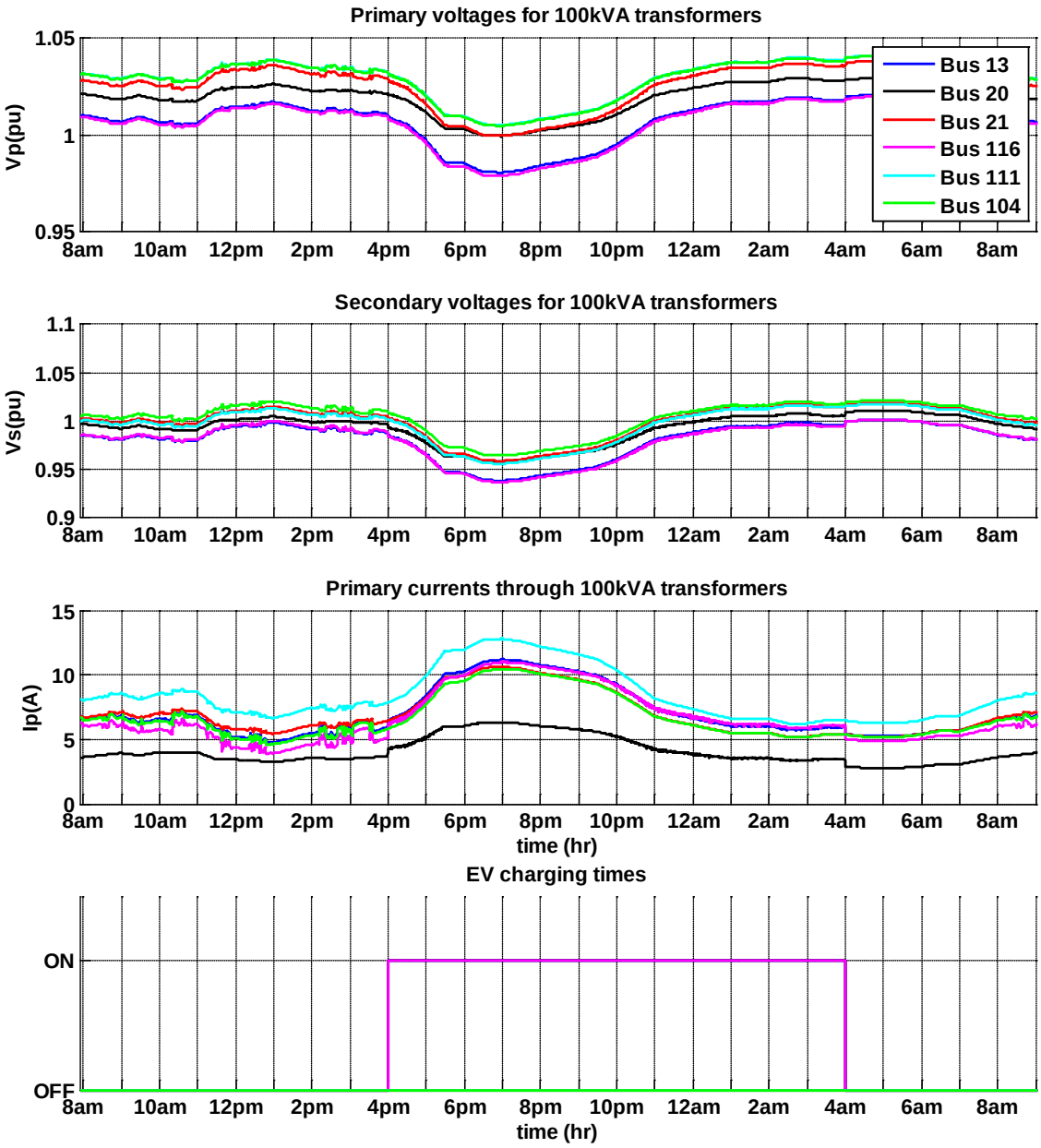

Figure 91 – Primary and secondary voltages and current at 100kVA transformers (EV Set 1, Always on)

3.10.2 EV Set 2, EV Always On

Voltages for the entire circuit are shown in *Figure 92*. Voltages for selected locations on each subsystem are shown in *Figure 93*. Transformer voltages and currents are shown in *Figure 94* through *Figure 97*. It was observed that EV charging had a large effect on primary transformer current flow, but only a minor effect on the secondary transformer voltage. EV charging had no significant effect on the circuit voltage.

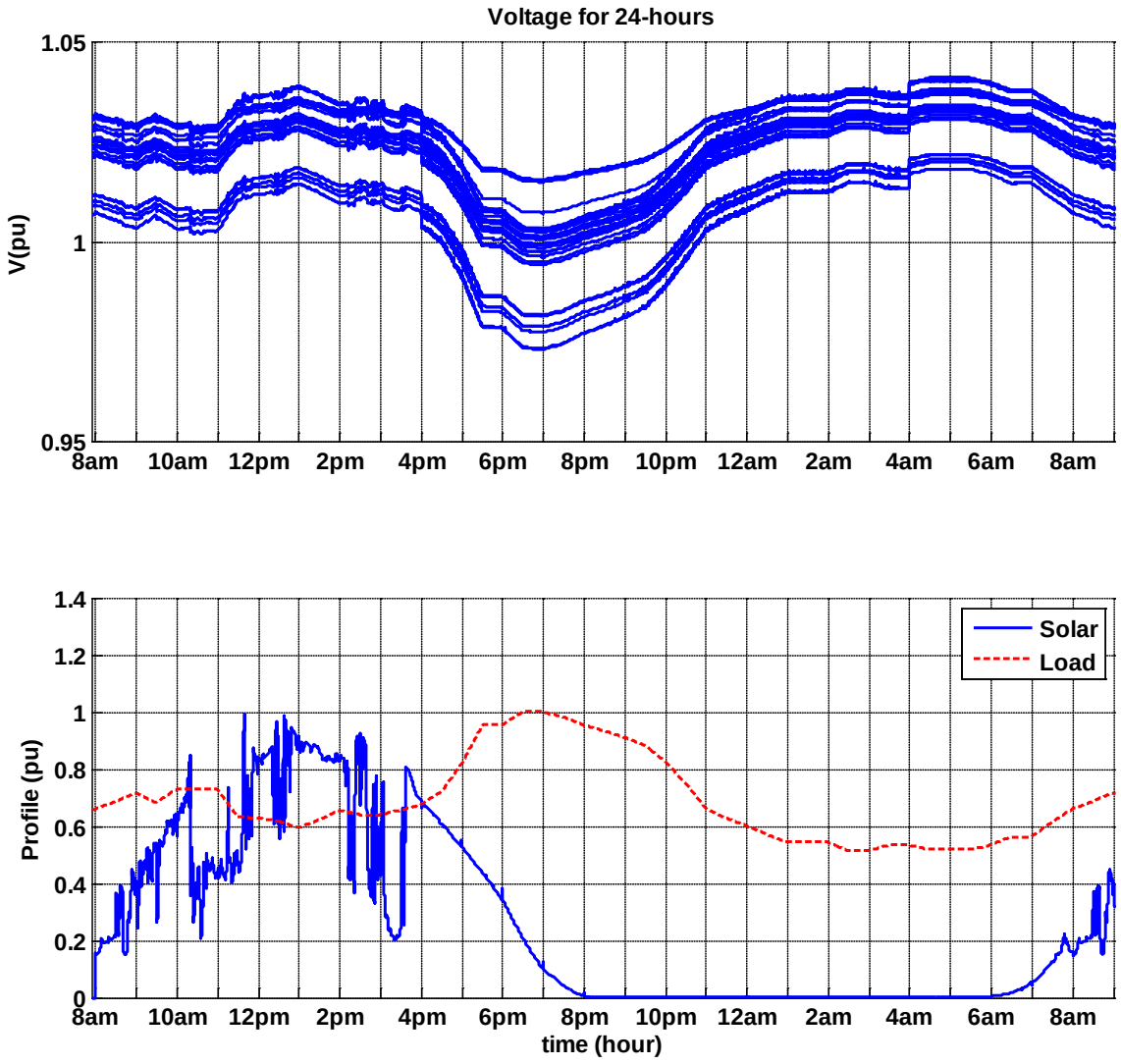

Figure 92 – Voltage at all circuit locations for varying load and PV profile (EV Set 2, Always on)

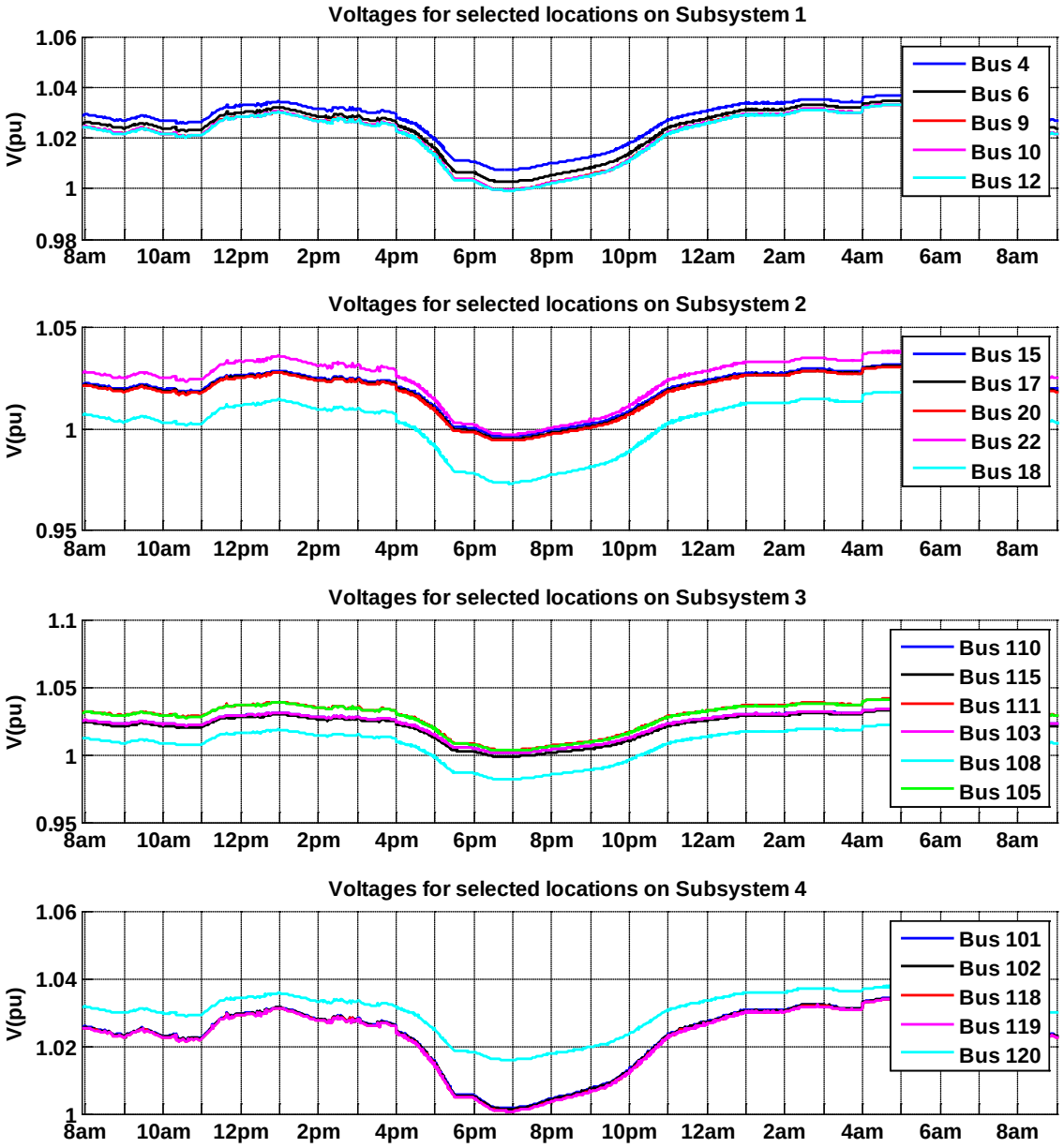

Figure 93 – Voltage at selected circuit locations for varying load and PV profile (EV Set 2, Always on)

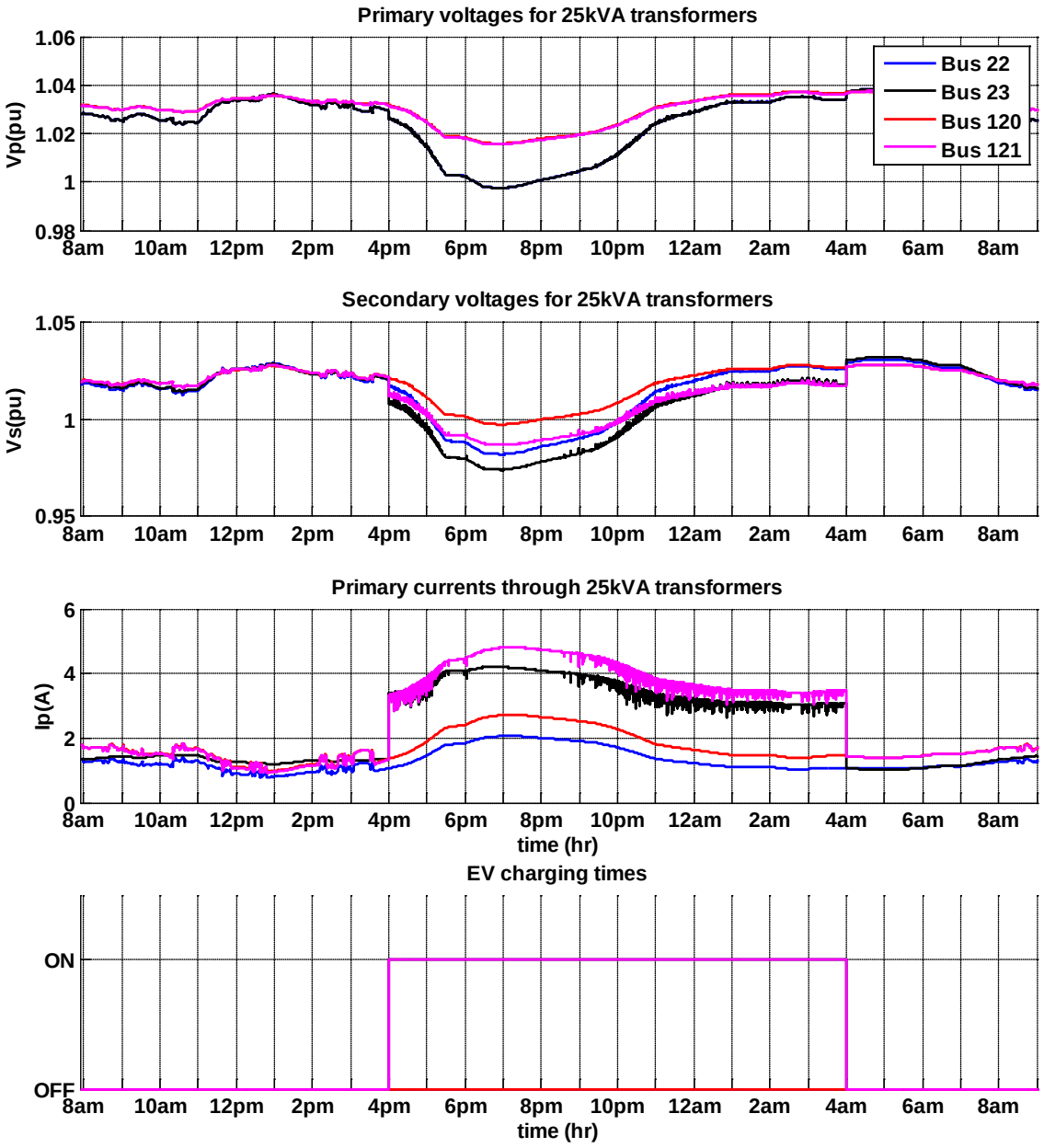

Figure 94 – Primary and secondary voltages and current at 25kVA transformers (EV Set 2, Always on)

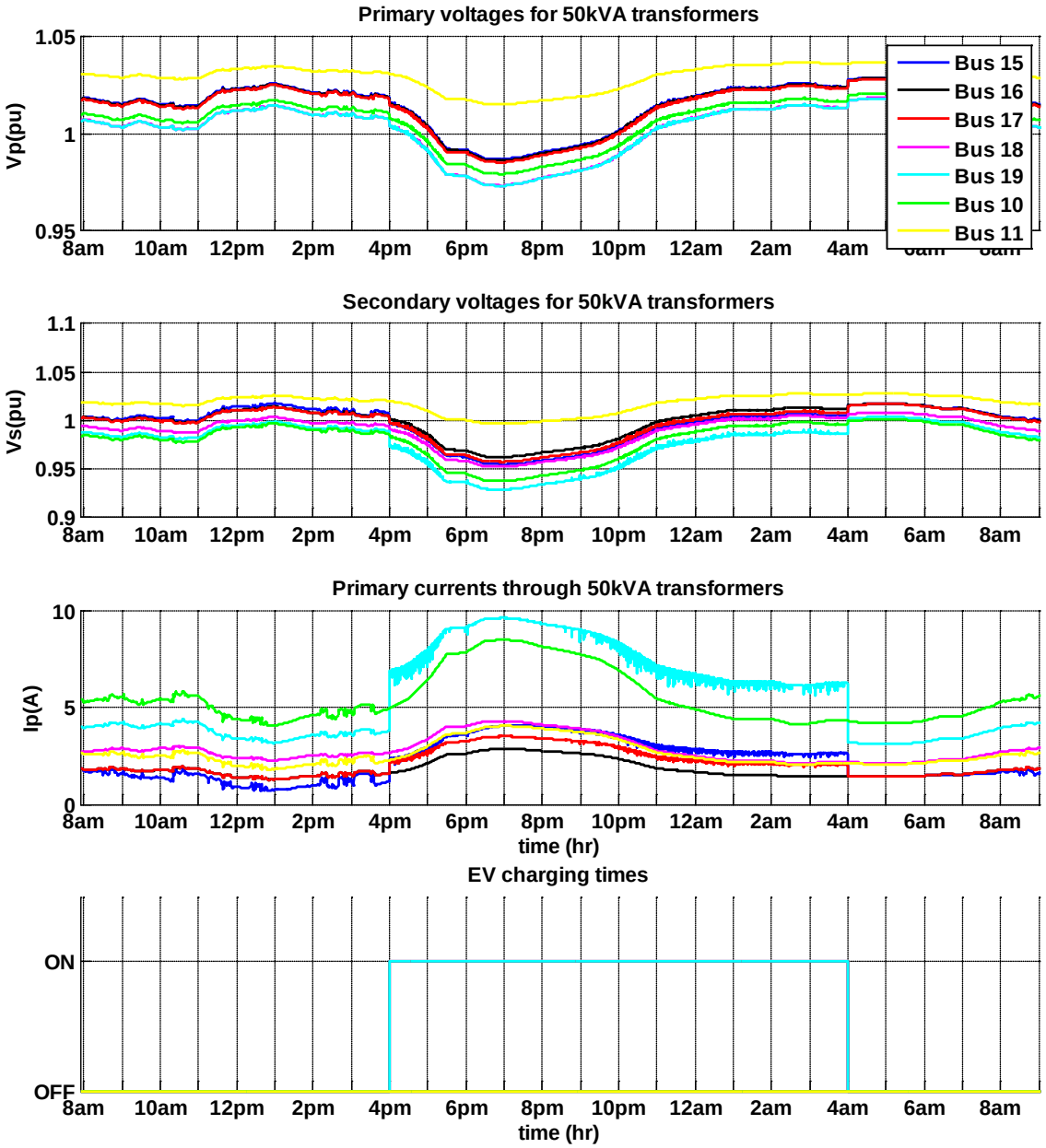

Figure 95 – Primary and secondary voltages and current at 50kVA transformers (EV Set 2, Always on)

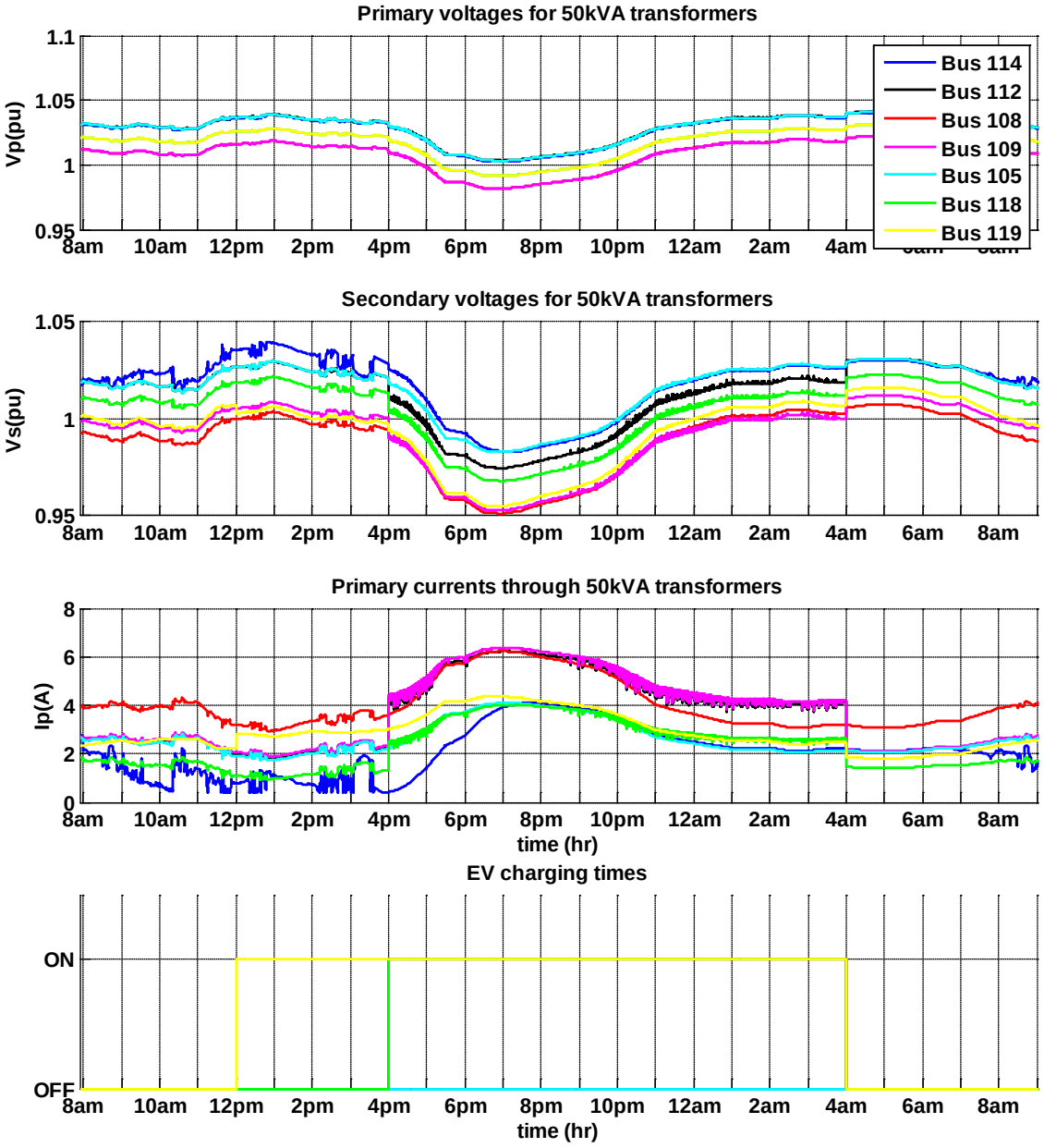

Figure 96 – Primary and secondary voltages and current at 50kVA transformers (EV Set 2, Always on)

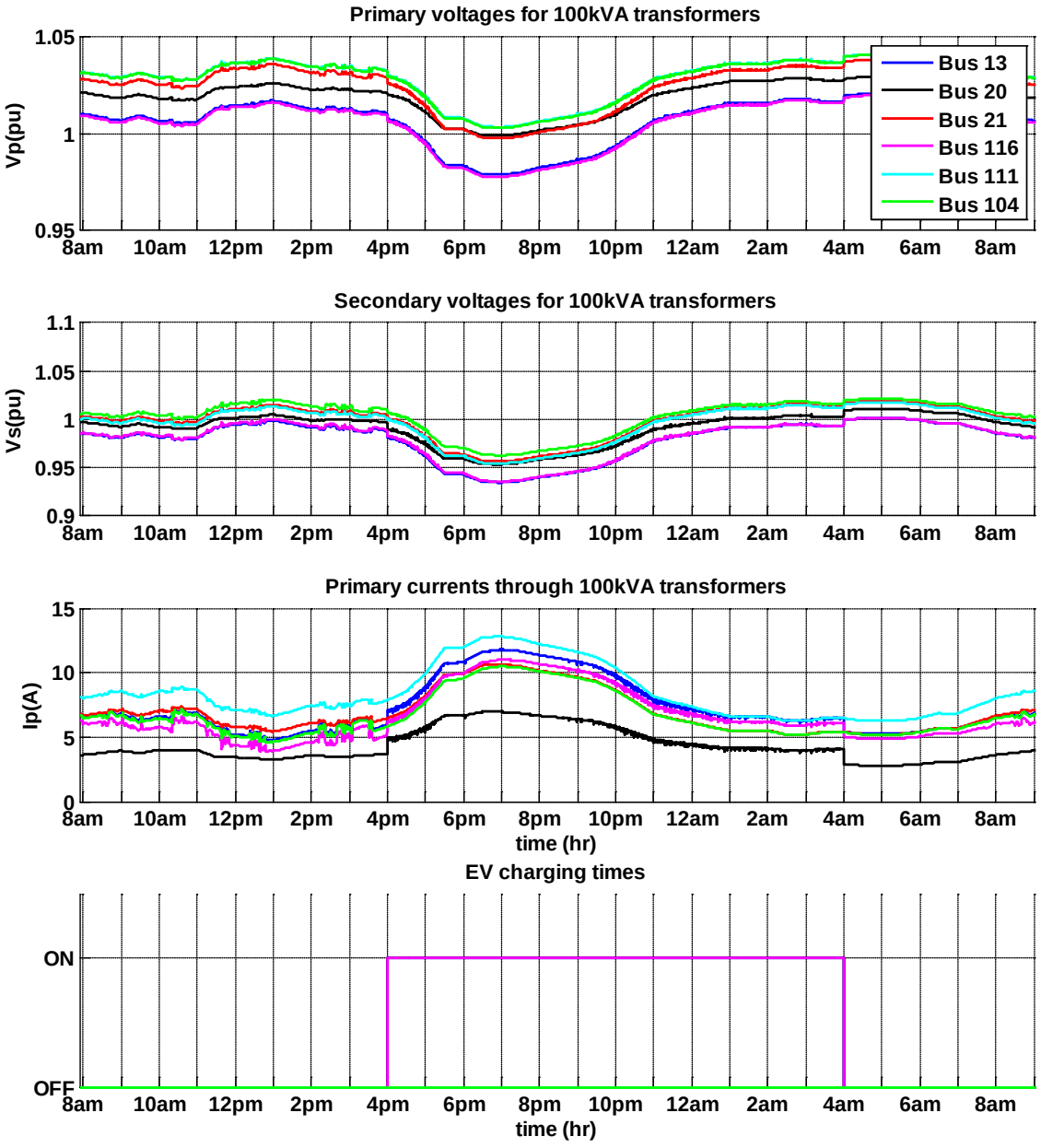

Figure 97 – Primary and secondary voltages and current at 100kVA transformers (EV Set 2, Always on)

3.10.1 EV Profile Set 1, Uncontrolled Charging

Voltages for the entire circuit are shown in *Figure 98*. Voltages for selected locations on each subsystem are shown in *Figure 99*. Transformer voltages and currents are shown in *Figure 100* through *Figure 119*. It was observed that EV charging had a large effect on primary transformer current flow, introducing about a 1% drop in the secondary transformer voltages.

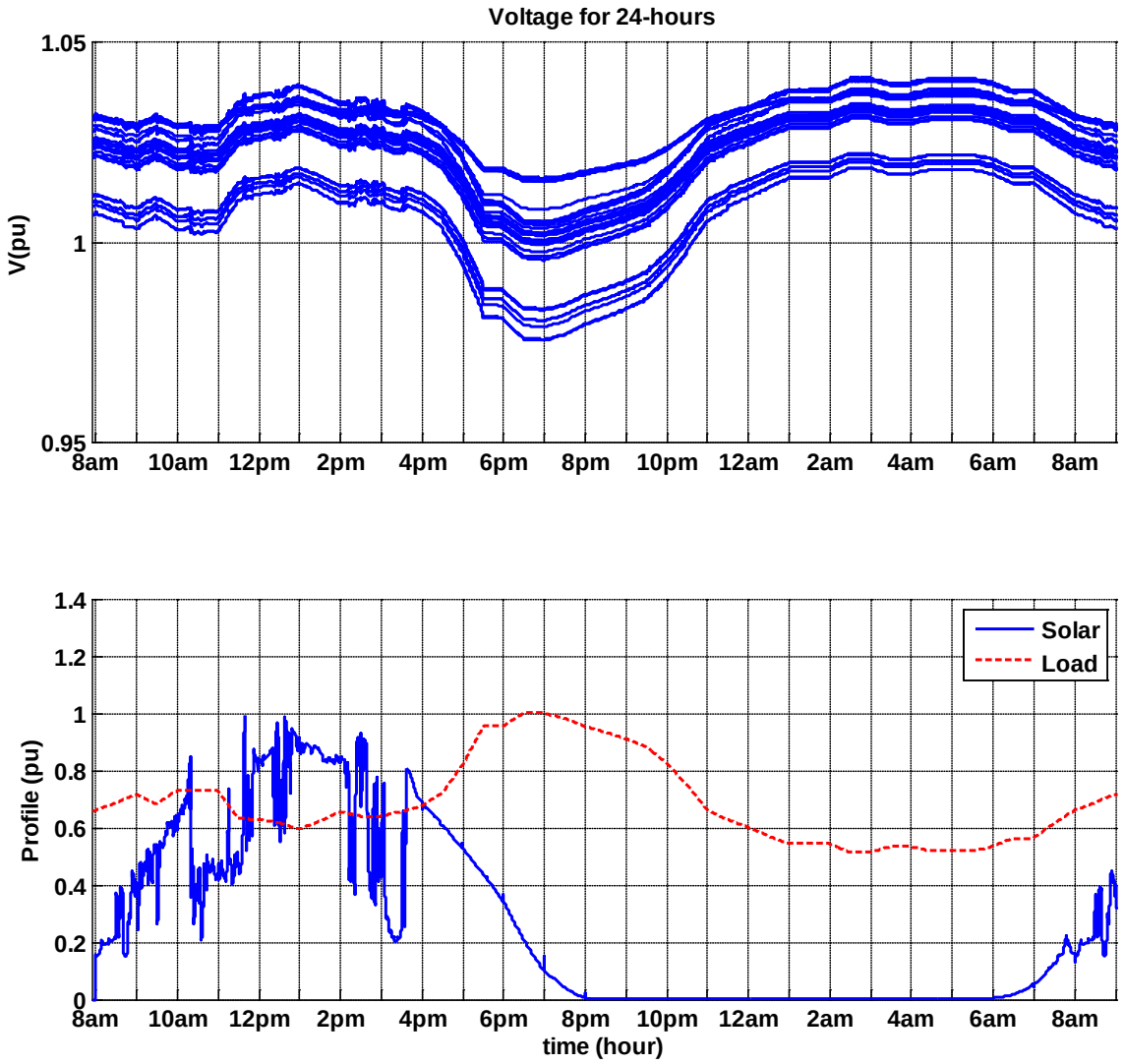

Figure 98 – Voltage at all circuit locations for varying load and PV profile (EV Set 1, Uncontrolled charging)

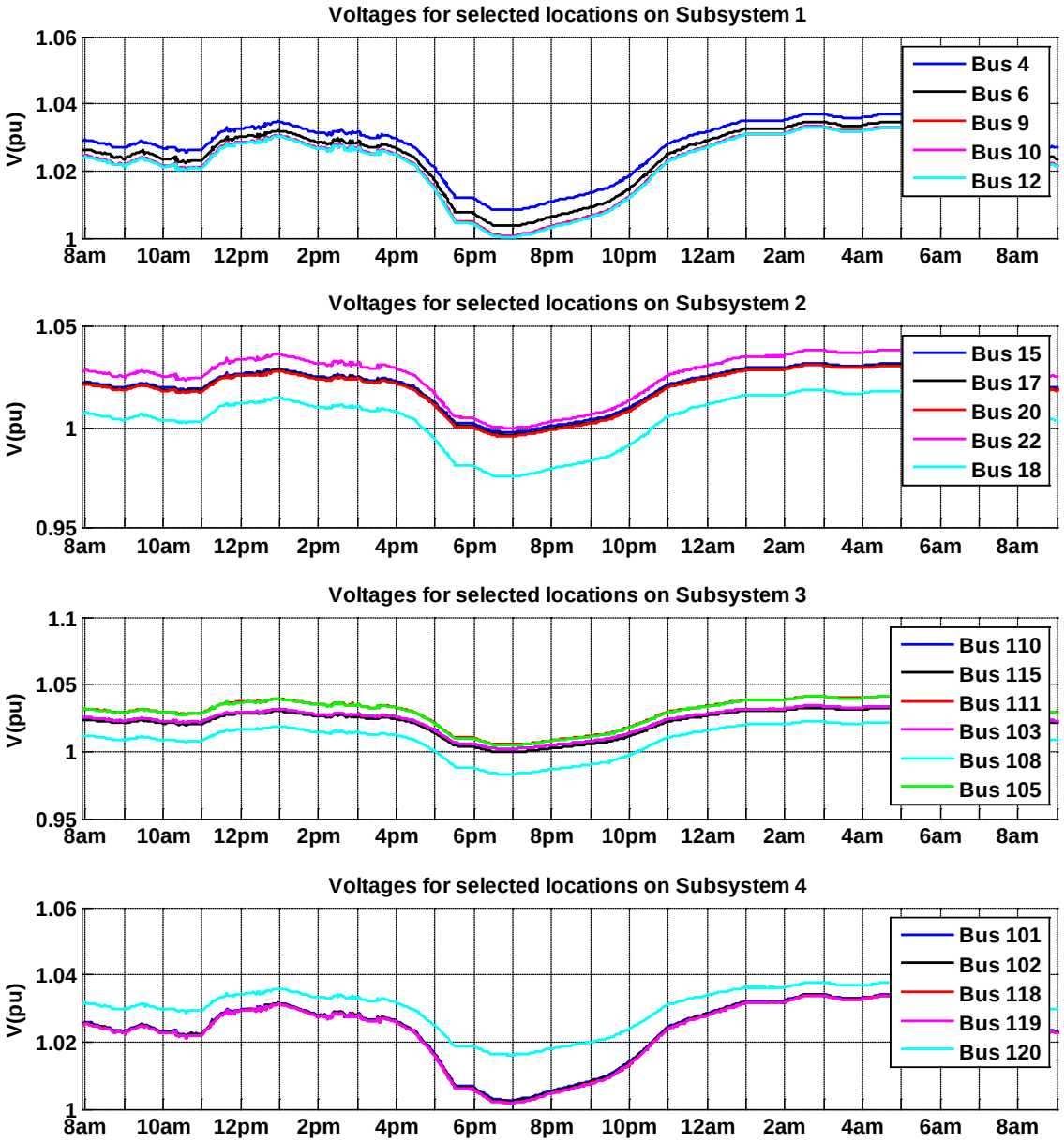

Figure 99 – Voltage at selected circuit locations for varying load and PV profile (EV Set 1, Uncontrolled charging)

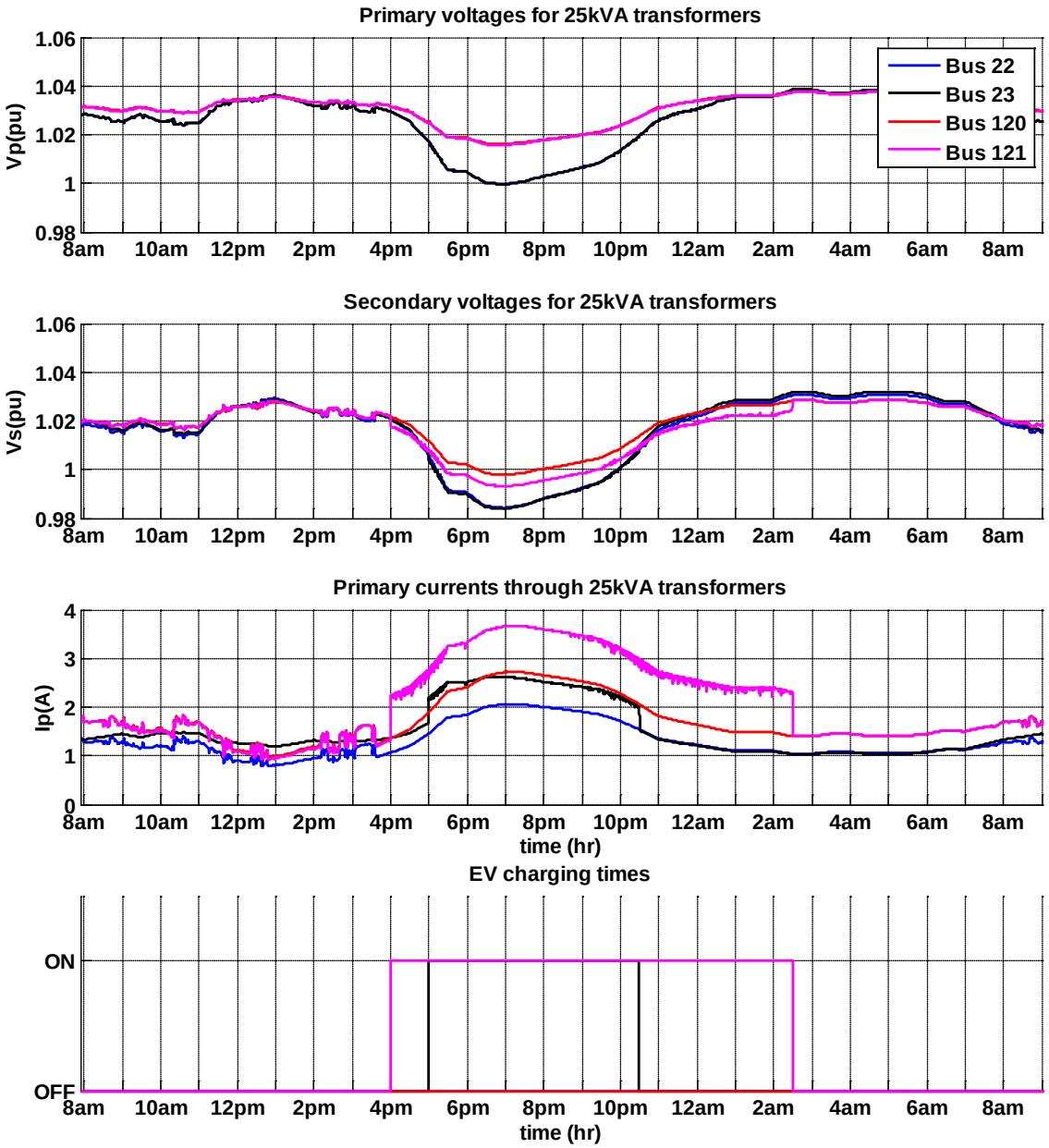

Figure 100 – Primary and secondary voltages and current at 25kVA transformers (EV Set 1, Uncontrolled charging)

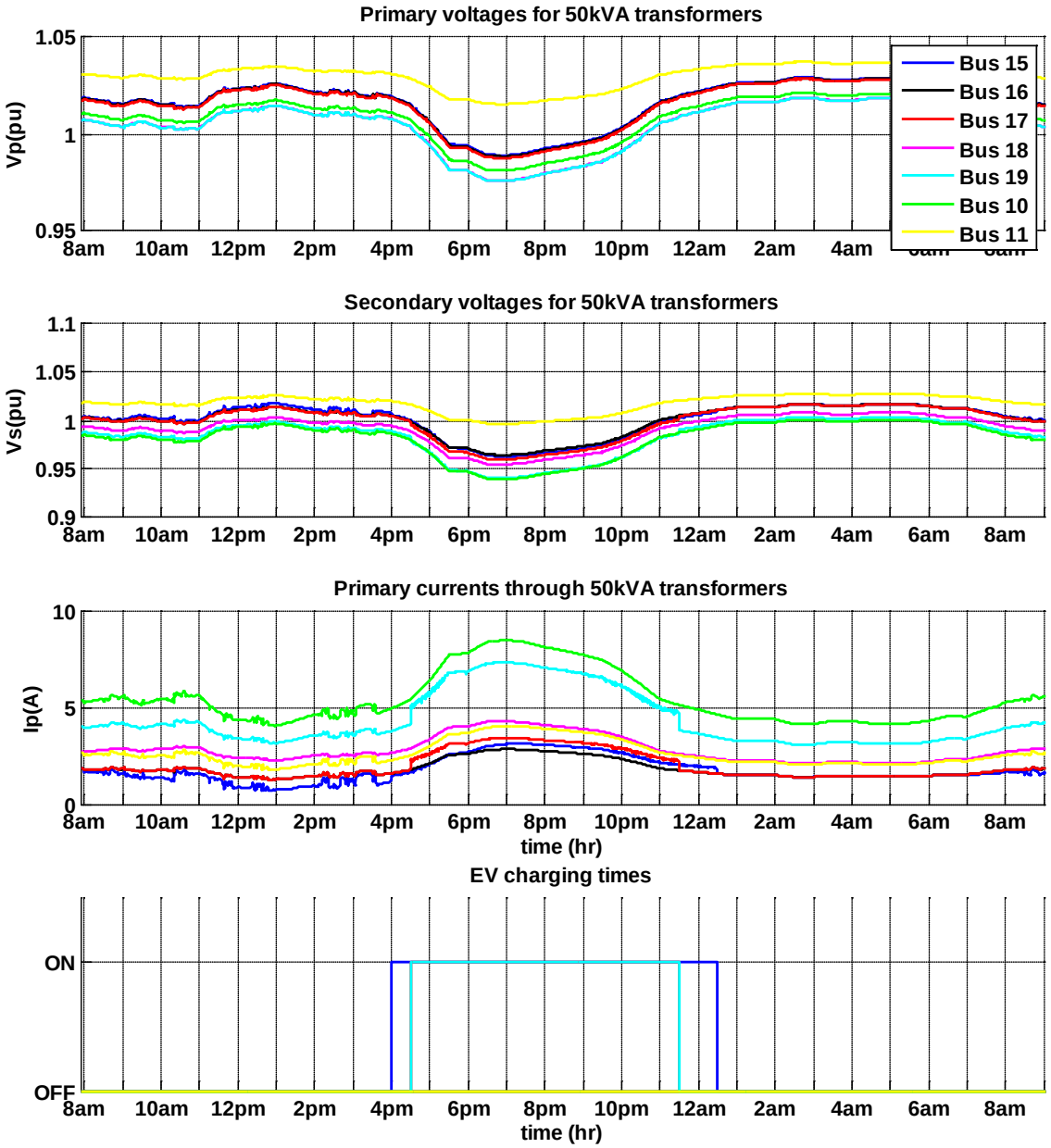

Figure 101 – Primary and secondary voltages and current at 50kVA transformers (EV Set 1, Uncontrolled charging)

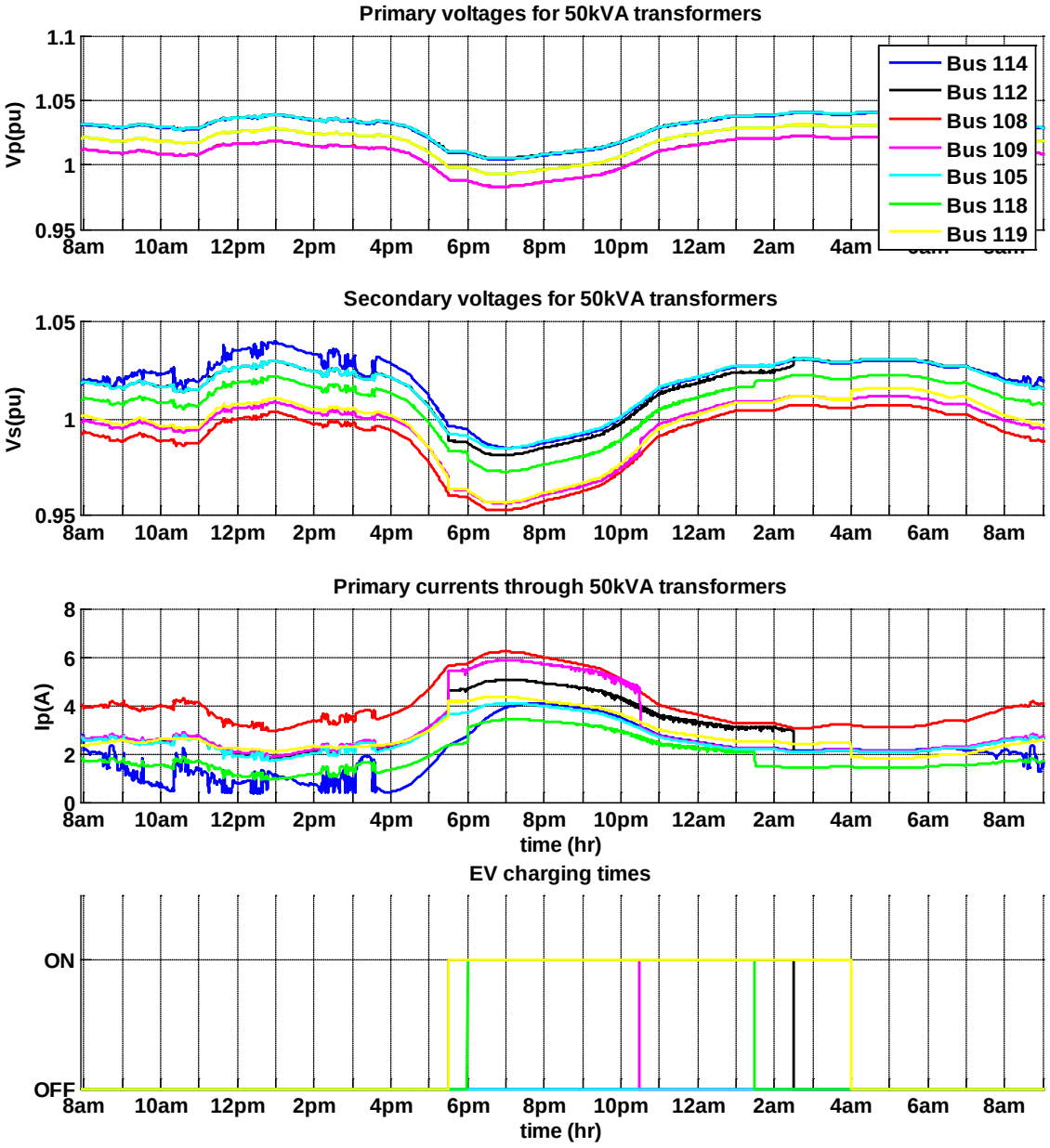

Figure 102 – Primary and secondary voltages and current at 50kVA transformers (EV Set 1, Uncontrolled charging)

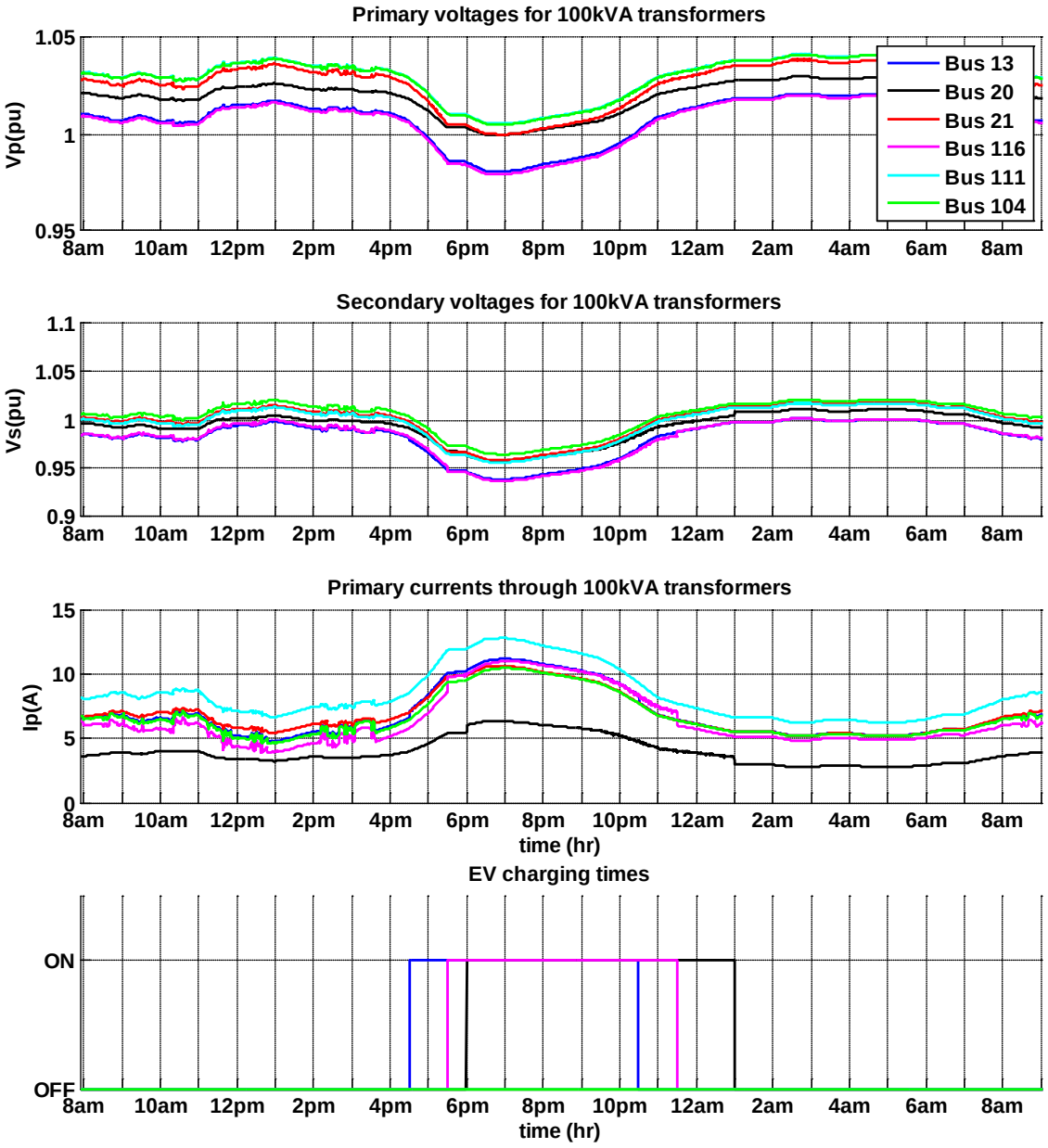

Figure 103 – Primary and secondary voltages and current at 100kVA transformers (EV Set 1, Uncontrolled charging)

3.10.1 EV Profile Set 2, Uncontrolled Charging

Voltages for the entire circuit are shown in *Figure 104*. Voltages for selected locations on each subsystem are shown in *Figure 105*. Transformer voltages and currents are shown in *Figure 106* through *Figure 109*. It was observed that EV charging had a large effect on primary transformer current flow, causing about a 1% drop in the secondary transformer voltages.

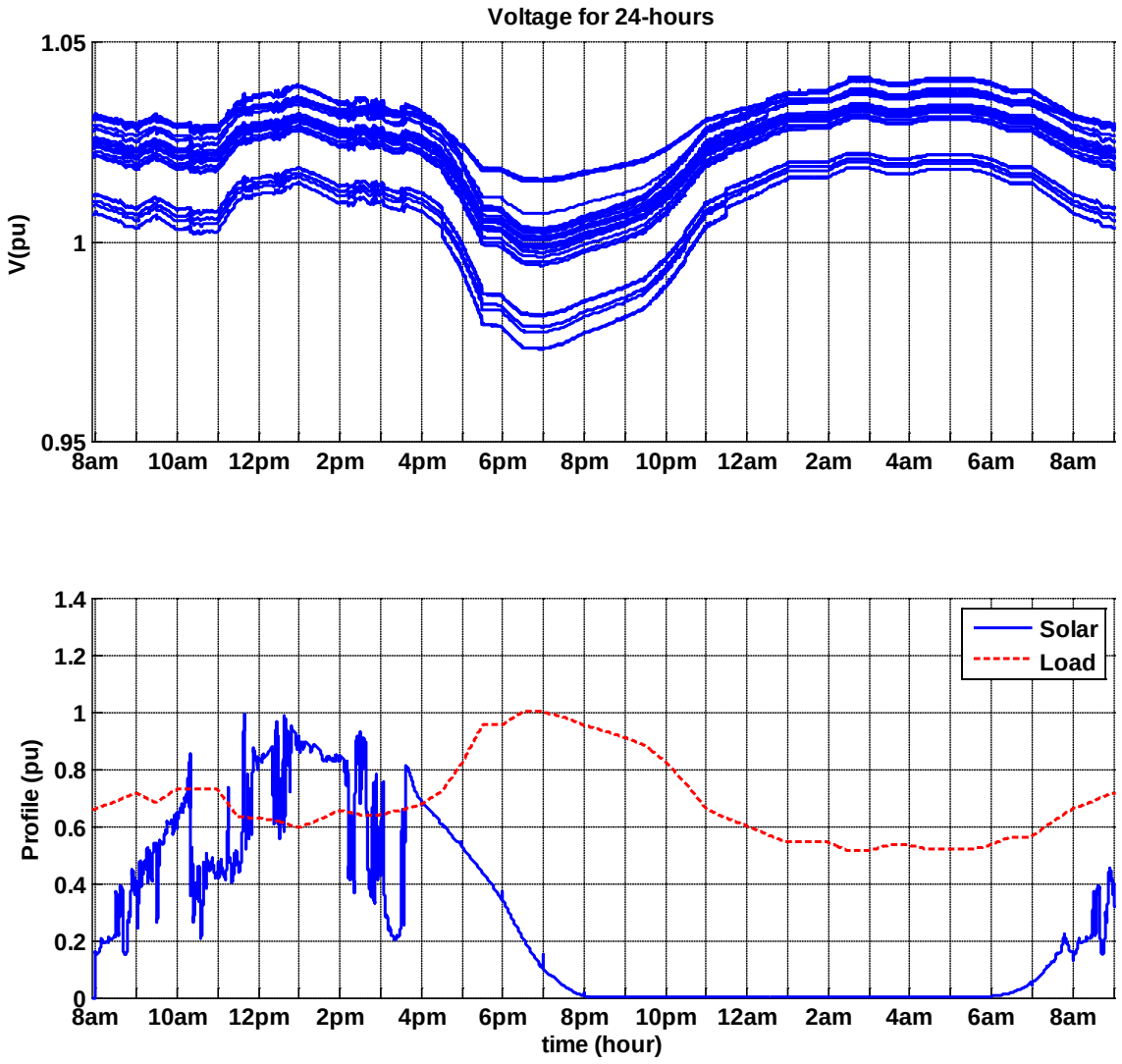

Figure 104 – Voltage at all circuit locations for varying load and PV profile (EV Set 2, Uncontrolled charging)

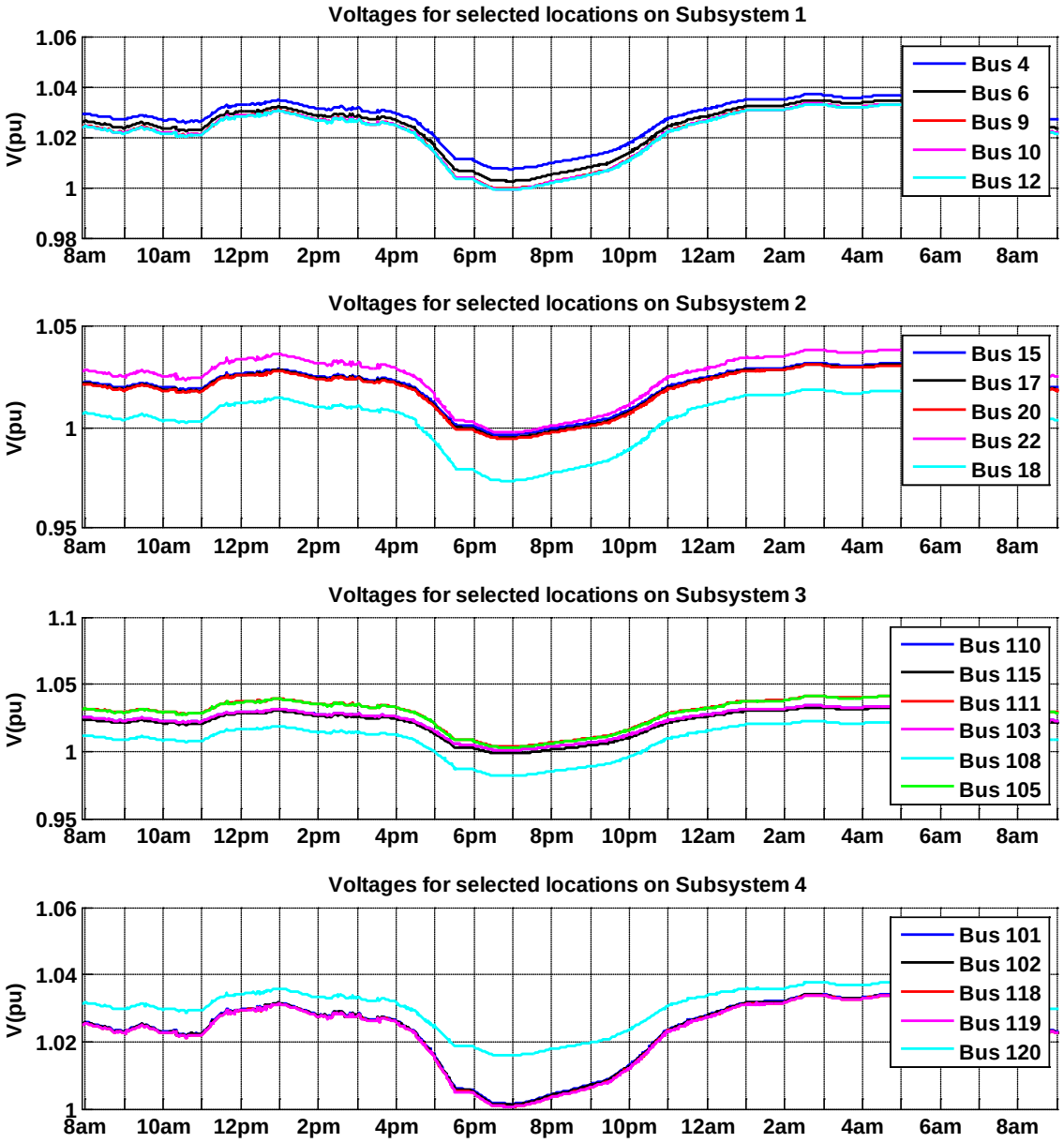

Figure 105 – Voltage at selected circuit locations for varying load and PV profile (EV Set 2, Uncontrolled charging)

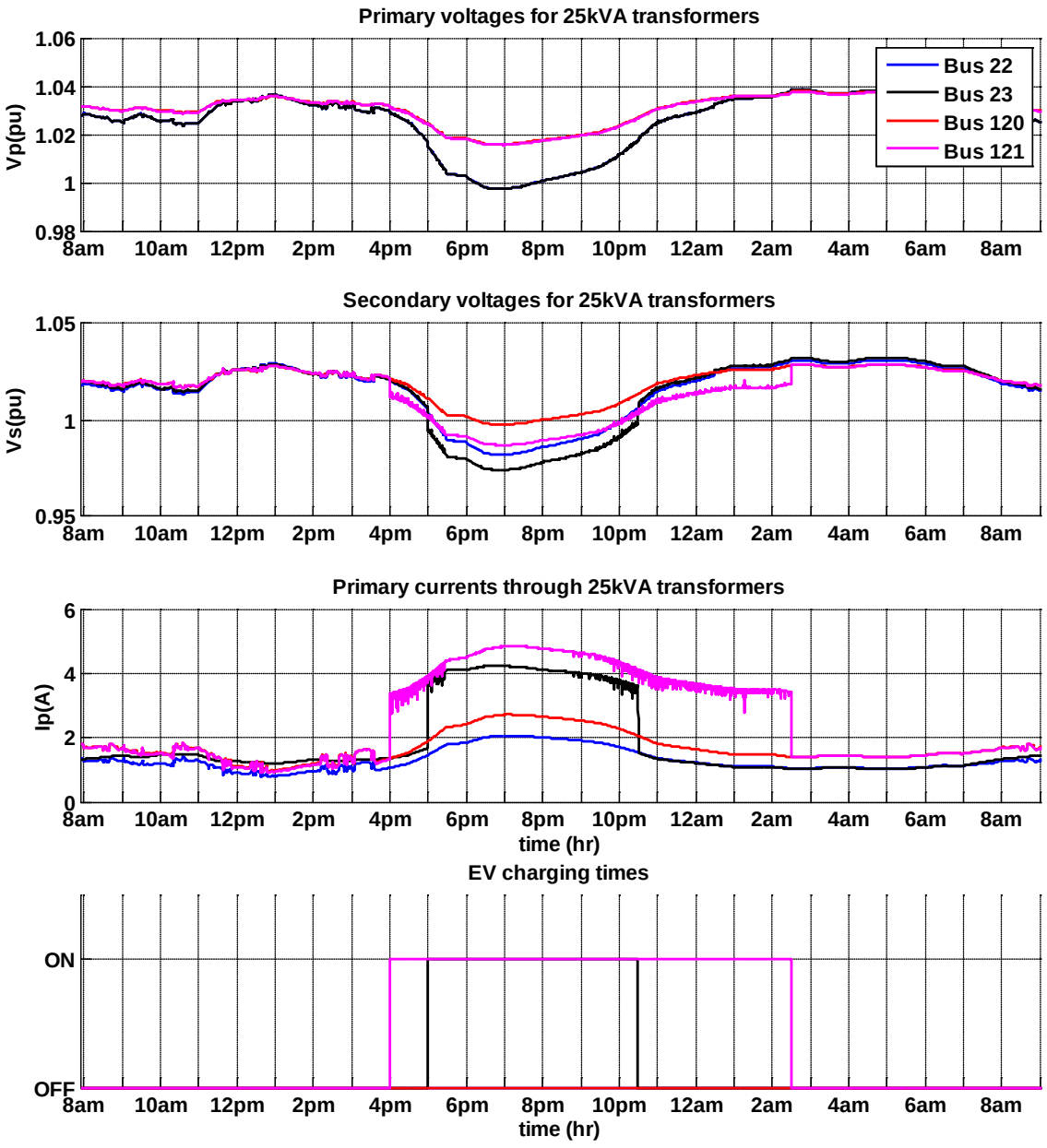

Figure 106 – Primary and secondary voltages and current at 25kVA transformers (EV Set 2, Uncontrolled charging)

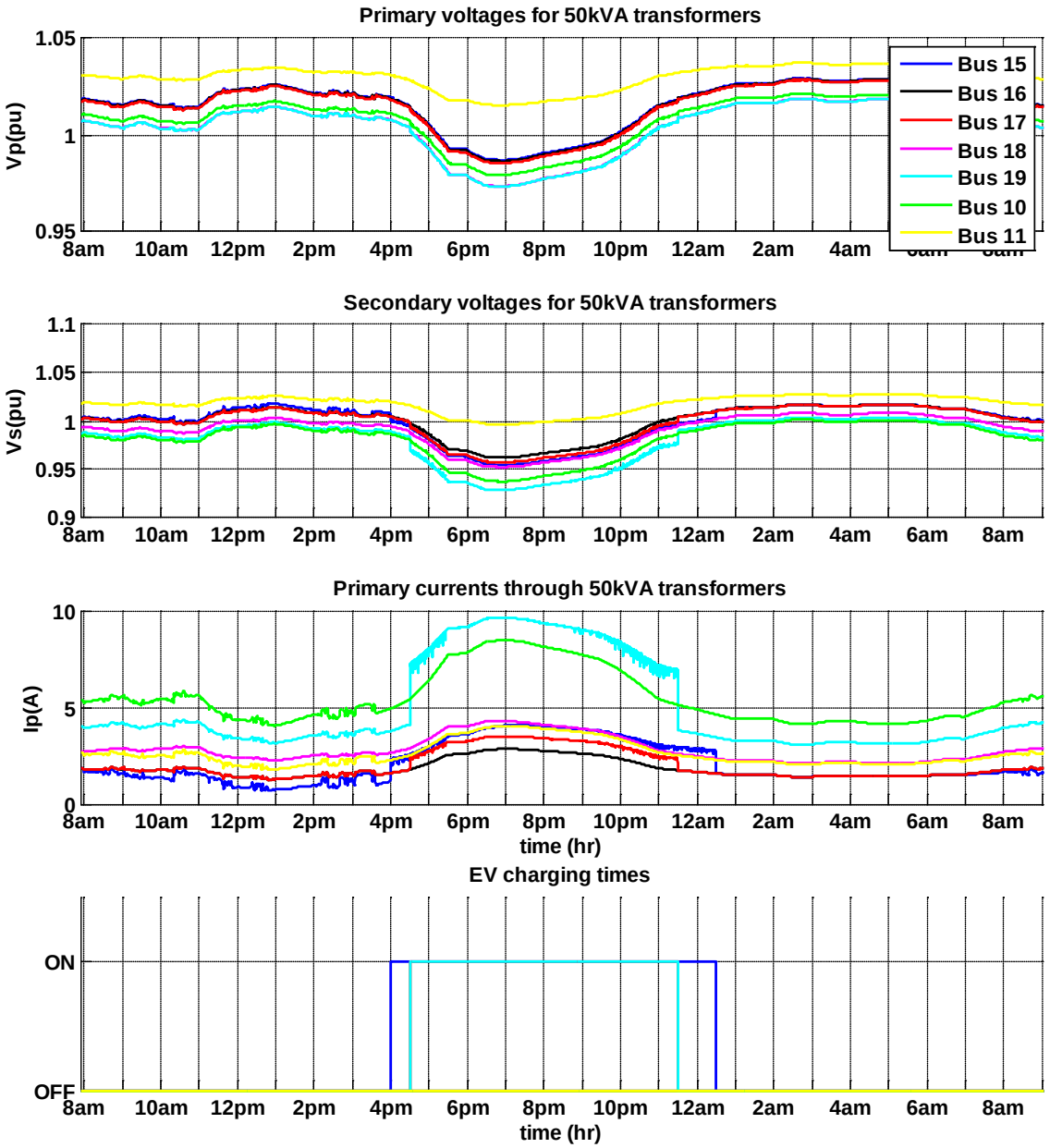

Figure 107 – Primary and secondary voltages and current at 50kVA transformers (EV Set 2, Uncontrolled charging)

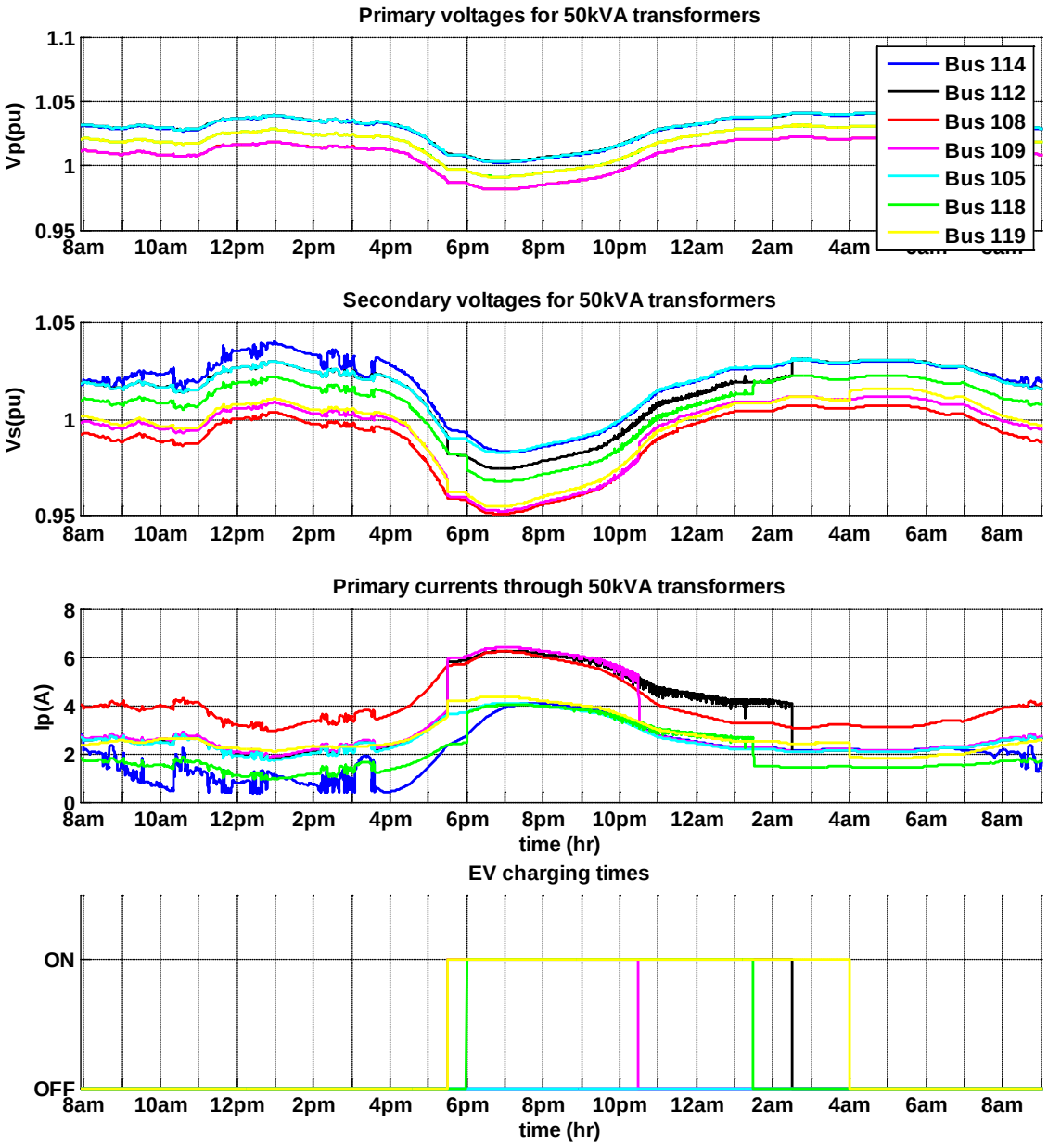

Figure 108 – Primary and secondary voltages and current at 50kVA transformers (EV Set 2, Uncontrolled charging)

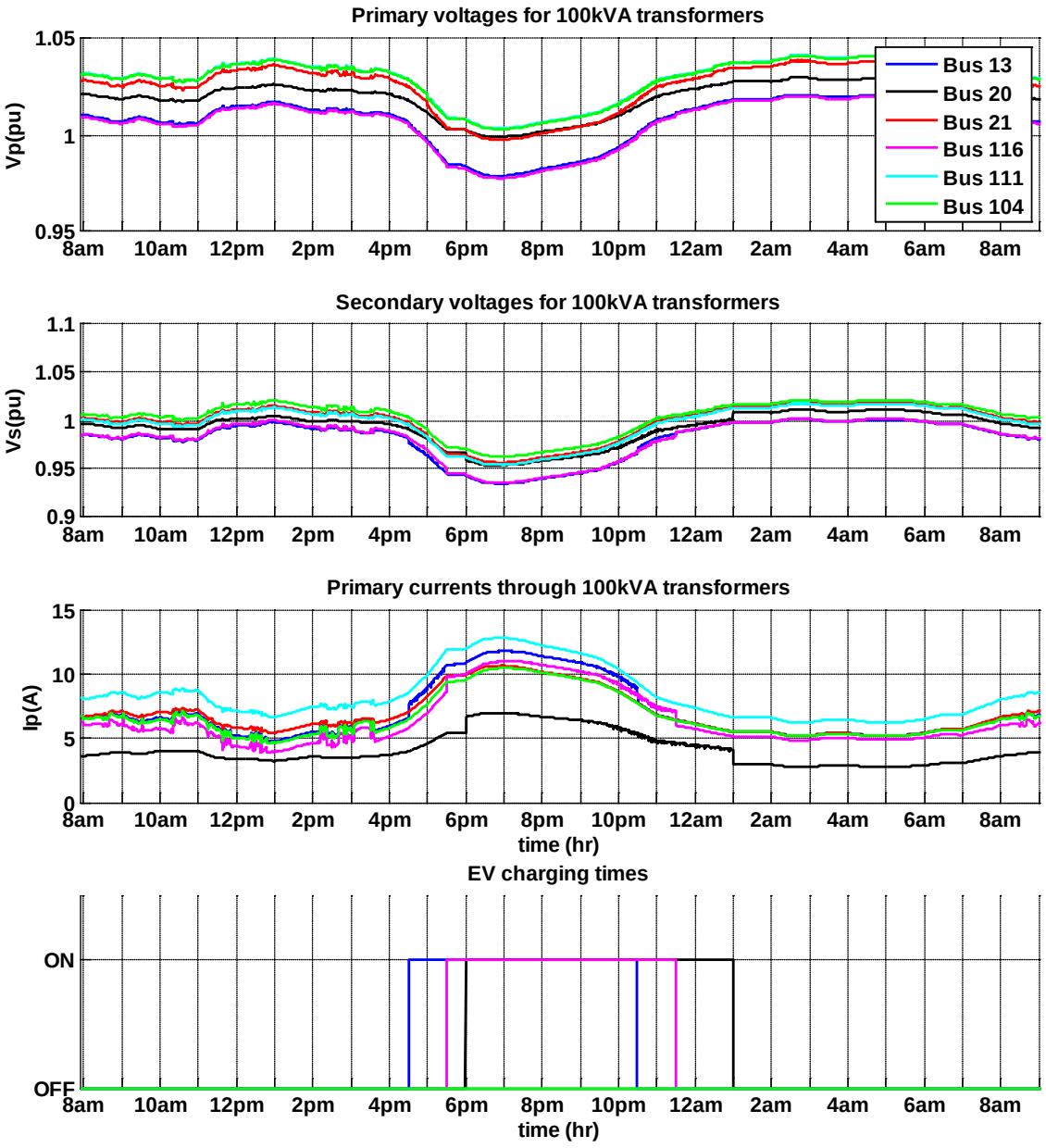

Figure 109 – Primary and secondary voltages and current at 100kVA transformers (EV Set 2, Uncontrolled charging)

3.11 *Online - Full system test – all customers have EV*

In this test, EV outputs were added to all customer locations (transformer secondary circuits). EV sizes and charging times were randomly assigned according the following sizes and times:

- EV Set 1: Random distribution of 3.3kW, 5.8kW, 6.6kW, 9.8kW EV sizes
- EV Set 2: 4x 3.5kV, 8x 6.8kV, 2x 9.8kV
- Always on: EV was charged from 16:00 (4:00pm) through to 4:00 (4:00am) the next morning
- Uncontrolled Charging: 16:00 – 18:00 starting times, 22:00 – 4:00 end times

The details for both EV size sets and uncontrolled charging times are given in ***Table 10***, with the original 14 EV customers being shaded.

Table 10 – EV size and charging times parameters for all customers

	Transformer Parameters			Load and PV			EV Size		EV Charging Time	
Bus #	XFMR kVA		Connection	Total Load		Total PV	Set 1	Set 2	Uncontrolled Charging	
	Rated	Actual		kW	kVAR	kW	kW	kW	Start	End
10	50	70	A	55	9	5.9	9.8	3.5	17:00	01:30
11	50	35	C	28	4	4.6	6.6	6.8	17:00	00:30
13	100	88	A	69	12	9.8	3.3	3.5	16:30	22:30
15	50	41	AB	55	10	12.7	3.3	6.8	16:00	00:30
16	50	41		56	9	5.0	5.8	9.8	17:00	01:00
17	50	41	AB	55	9	6.0	5.8	3.5	16:30	23:30
20	100	82	AC	235	41		6.6	6.8	18:00	01:00
21	100	89	B	70	12	4.7	5.8	6.8	16:30	03:00
22	25	16	B	14	3	3.3	9.8	3.5	16:30	03:00
23	25	18	B	14	2		3.3	6.8	17:00	22:30
18	50	35	A	28	5	1.5	3.3	6.8	16:00	22:00
19	50	32	A	41	7	3.3	5.8	9.8	16:30	23:30
113	50	35	C	28	5	27.5	6.6	6.8	16:00	02:00
114	50	36	B	29	6	5.0	5.8	6.8	16:30	01:30
116	100	82	A	137	24	13.2	6.6	3.5	17:30	23:30
111	100	108	B	84	14	4.6	5.8	6.8	16:00	23:00
112	50	35	B	28	5	4.7	5.8	6.8	17:30	02:30
107	50	52	A	41	7	5.2	5.8	3.5	17:30	00:00
108	50	52	A	41	7	4.9	6.6	6.8	18:00	03:00
109	50	35	A	28	5	4.3	9.8	6.8	17:30	22:30
104	100	89	B	70	12	10.9	9.8	9.8	17:00	02:30
105	50	35	B	28	5	5.2	5.8	3.5	18:00	23:30
106	25	17	B	14	2		9.8	9.8	17:00	00:30
118A	50	41	AB	55	10	9.5	6.6	6.8	18:00	01:30
118B	50	46	BC	260	10	9.5	9.8	6.8	16:30	02:00
119	50	53	AB	42	7		6.6	3.5	17:30	04:00
120	25	24	C	19	3	5.1	9.8	6.8	17:30	00:30
121	25	24	C	19	3	5.4	5.8	6.8	16:00	02:30

3.11.1 EV Profile Set 1, EV Always On

Voltages for the entire circuit are shown in *Figure 110*. Voltages for selected locations on each subsystem are shown in *Figure 111*. Transformer voltages and currents are shown in *Figure 112* through *Figure 115*. It was observed that EV charging had a large effect on primary transformer current flow, causing the secondary transformer voltage minor drop. EV charging had less effect on the circuit voltage.

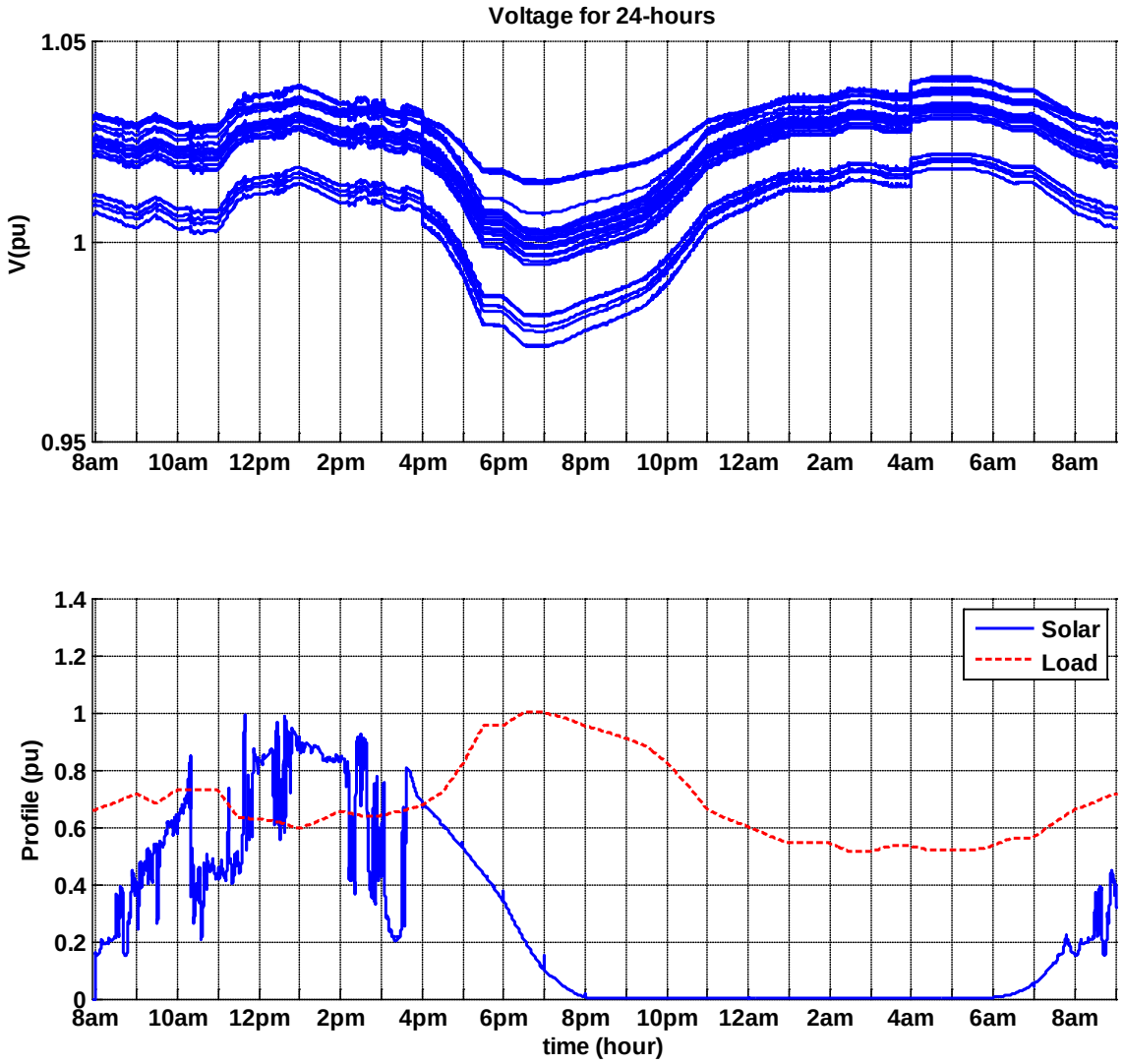

Figure 110 – Voltage at all circuit locations for varying load and PV profile (EV Set 1, Always on)

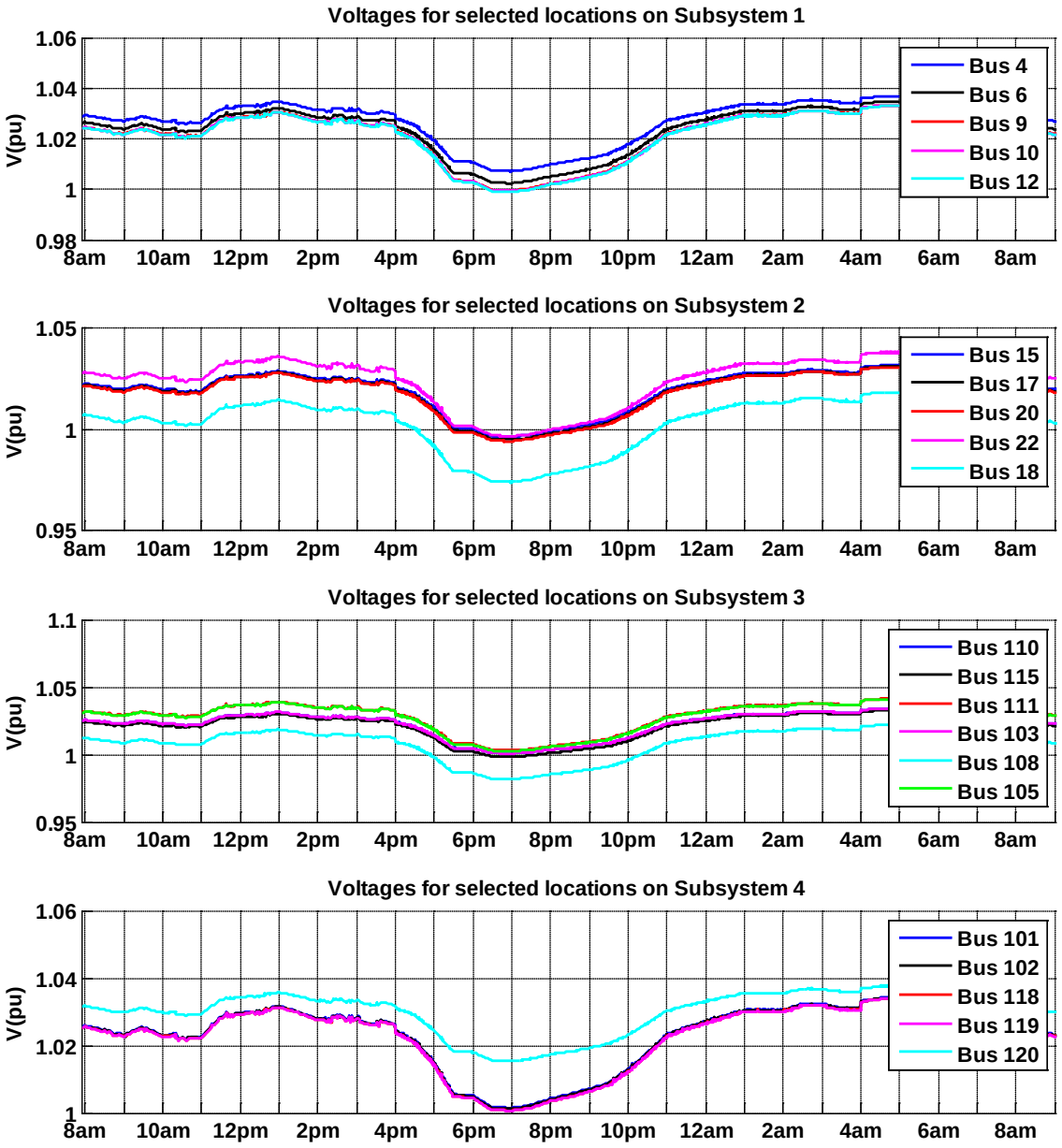

Figure 111 – Voltage at selected circuit locations for varying load and PV profile (EV Set 1, Always on)

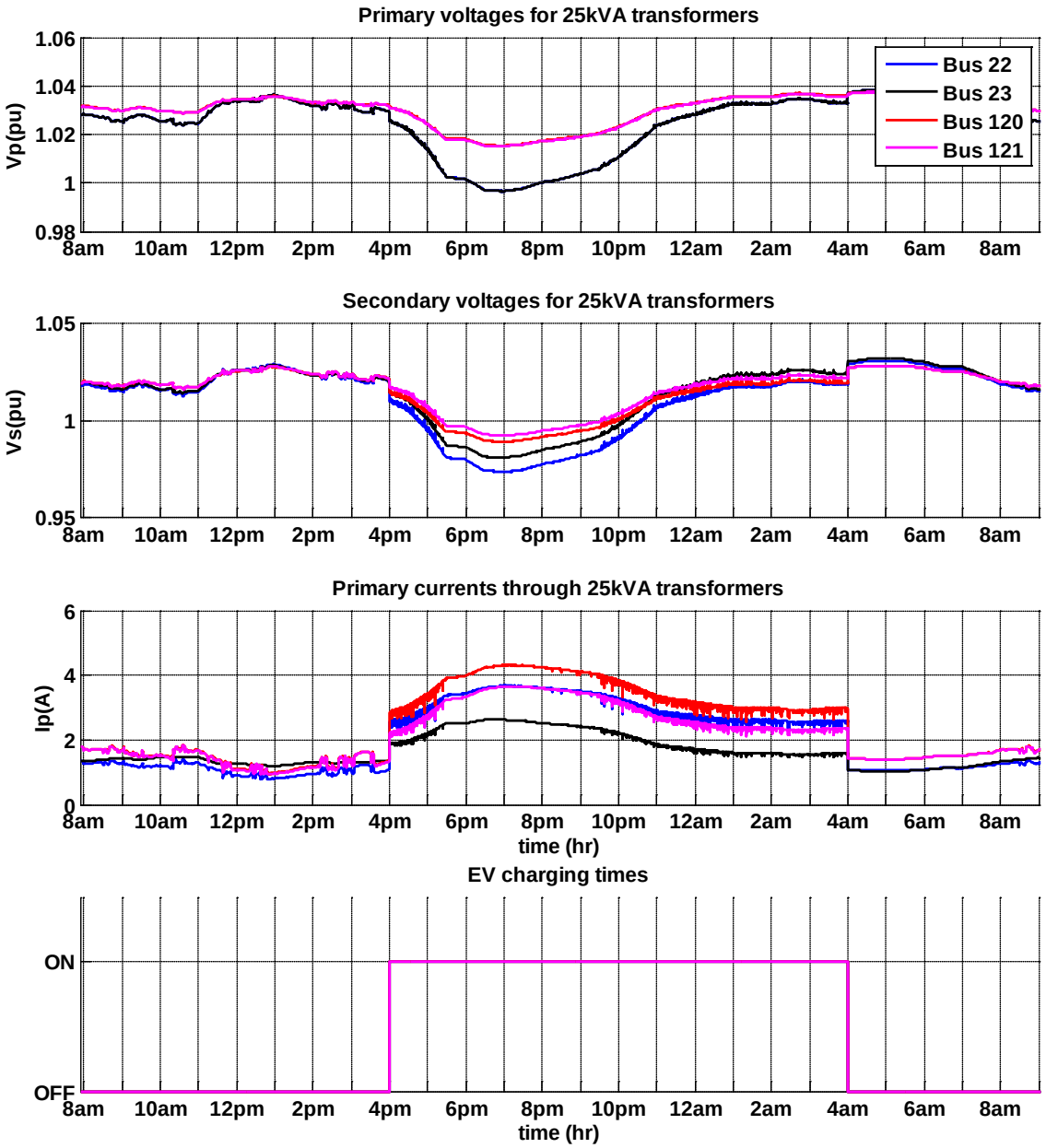

Figure 112 – Primary and secondary voltages and current at 25kVA transformers (EV Set 1, Always on)

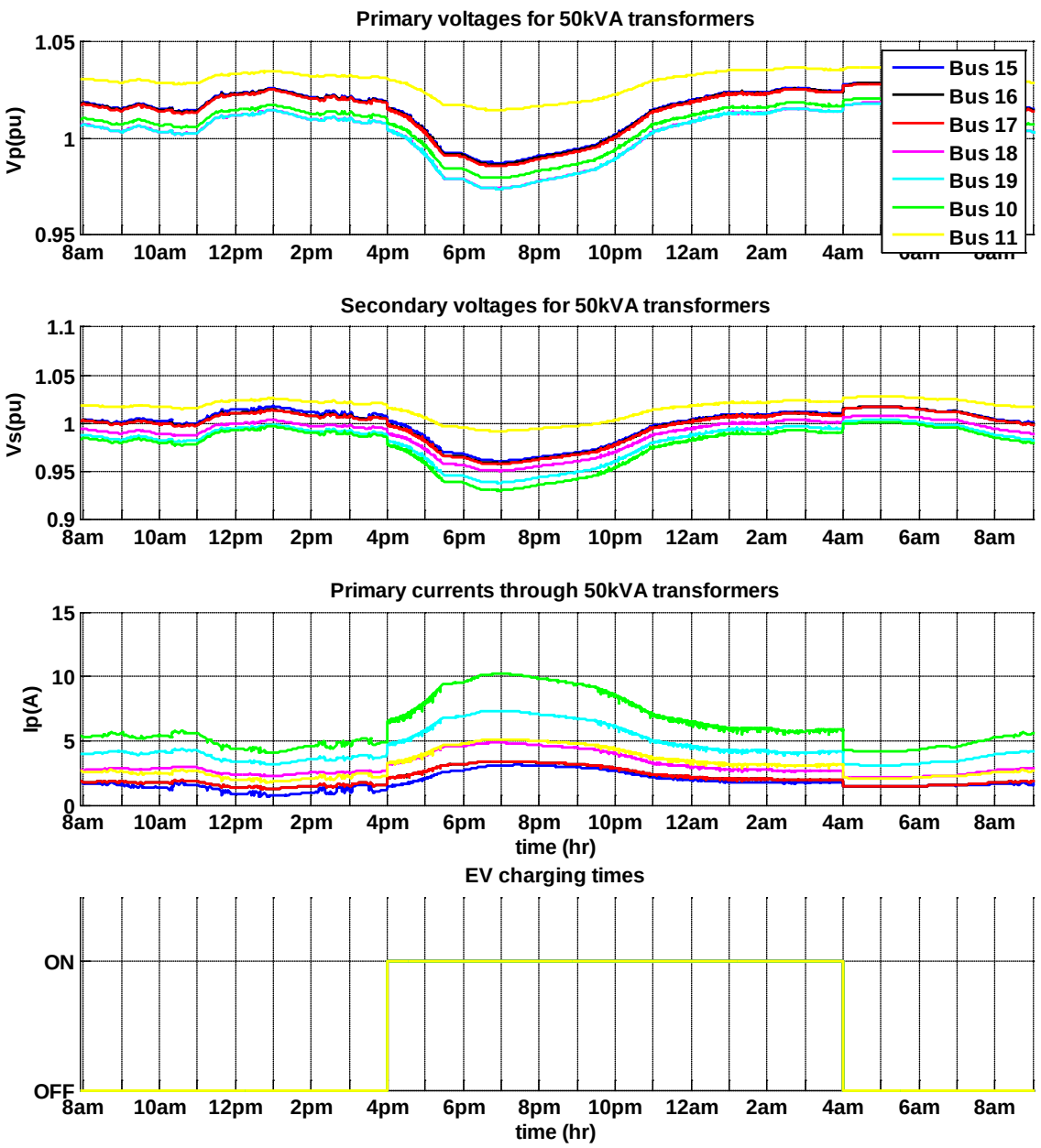

Figure 113 – Primary and secondary voltages and current at 50kVA transformers (EV Set 1, Always on)

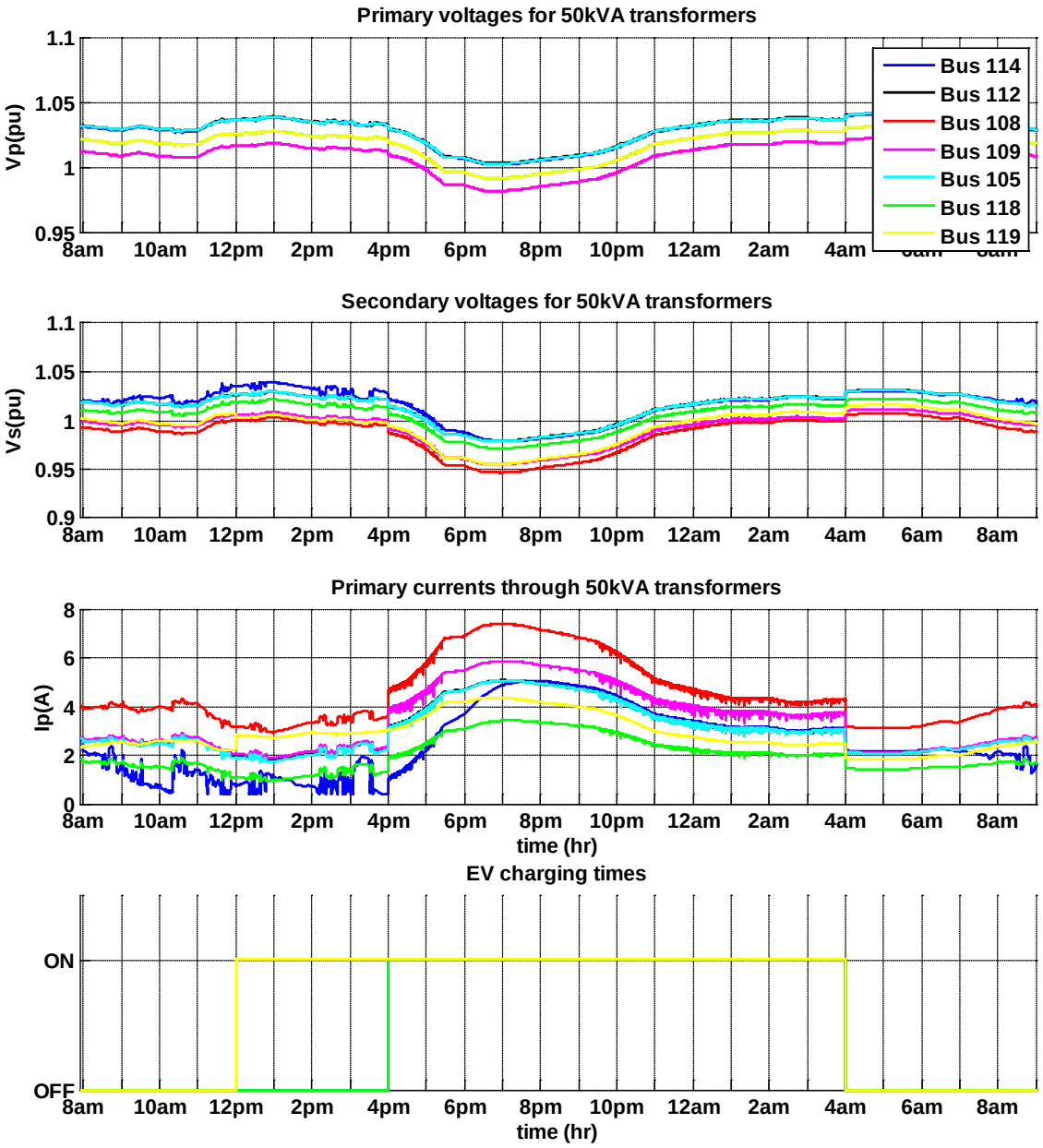

Figure 114 – Primary and secondary voltages and current at 50kVA transformers (EV Set 1, Always on)

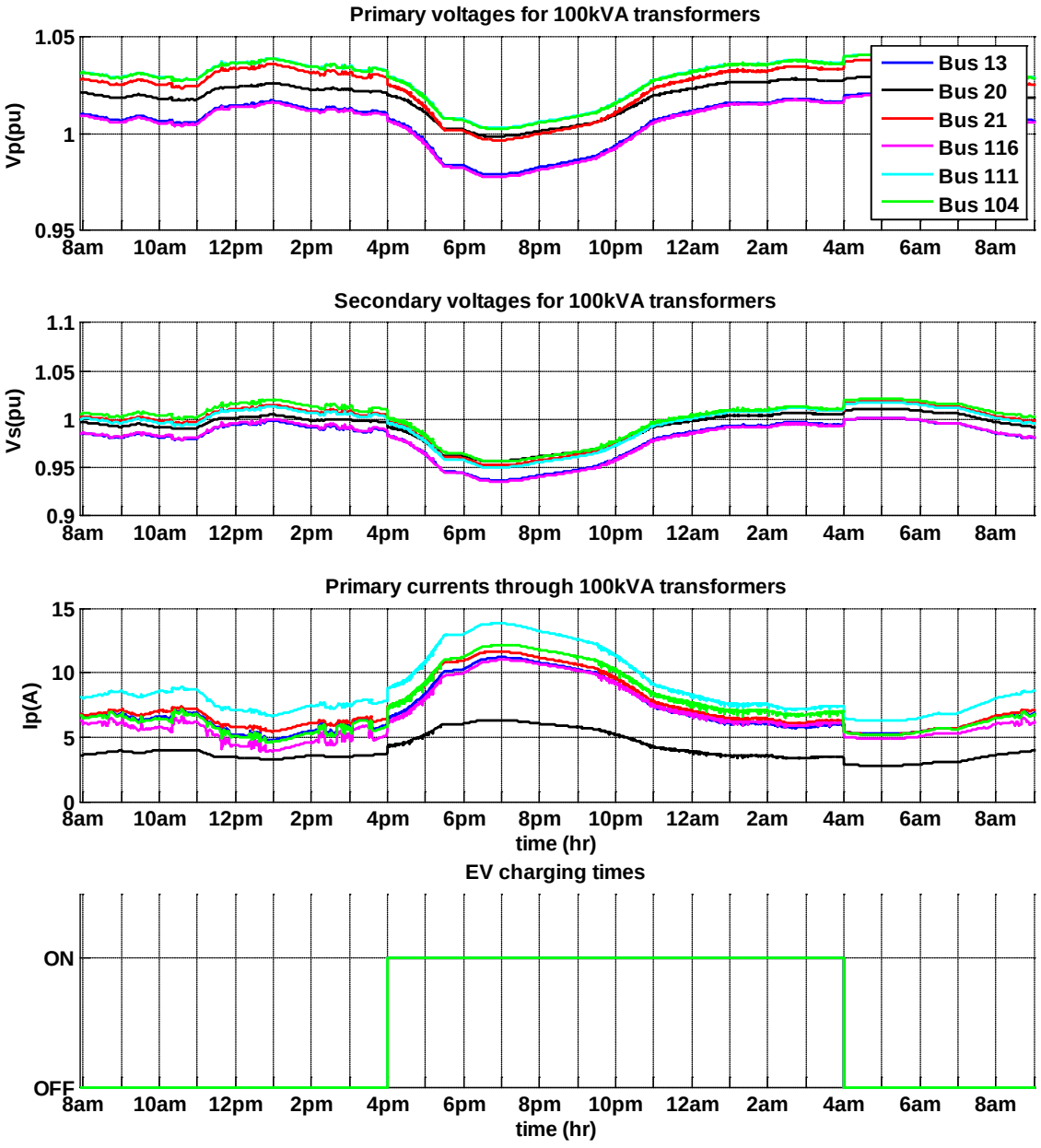

Figure 115 – Primary and secondary voltages and current at 100kVA transformers (EV Set 1, Always on)

3.11.2 EV Set 2, EV Always On

Voltages for the entire circuit are shown in *Figure 116*. Voltages for selected locations on each subsystem are shown in *Figure 117*. Transformer voltages and currents are shown in *Figure 118* through *Figure 121*. It was observed that EV charging had a large effect on primary transformer current flow, but only a minor effect on the secondary transformer voltage. EV charging had less effect on the primary circuit voltage.

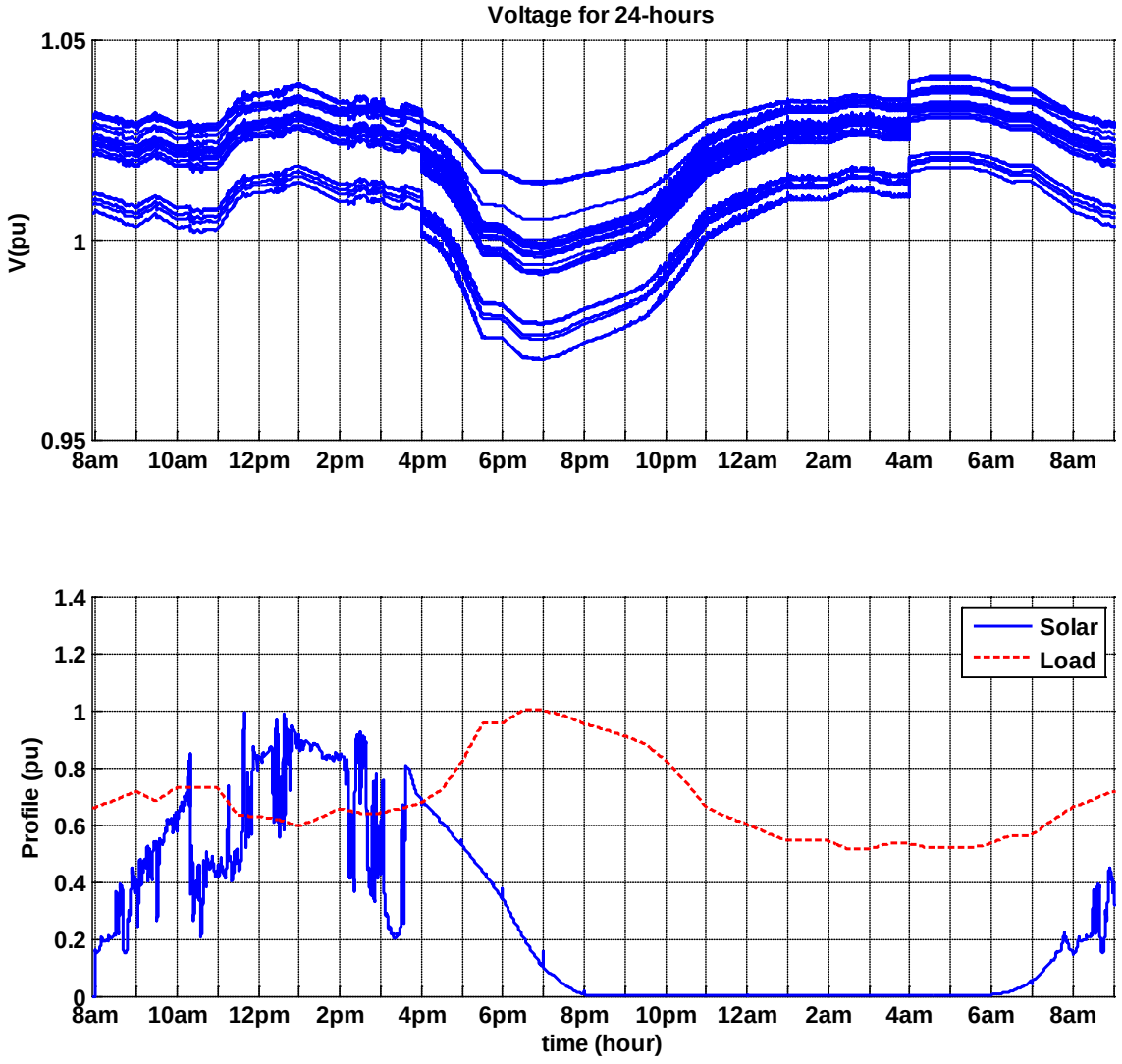

Figure 116 – Voltage at all circuit locations for varying load and PV profile (EV Set 2, Always on)

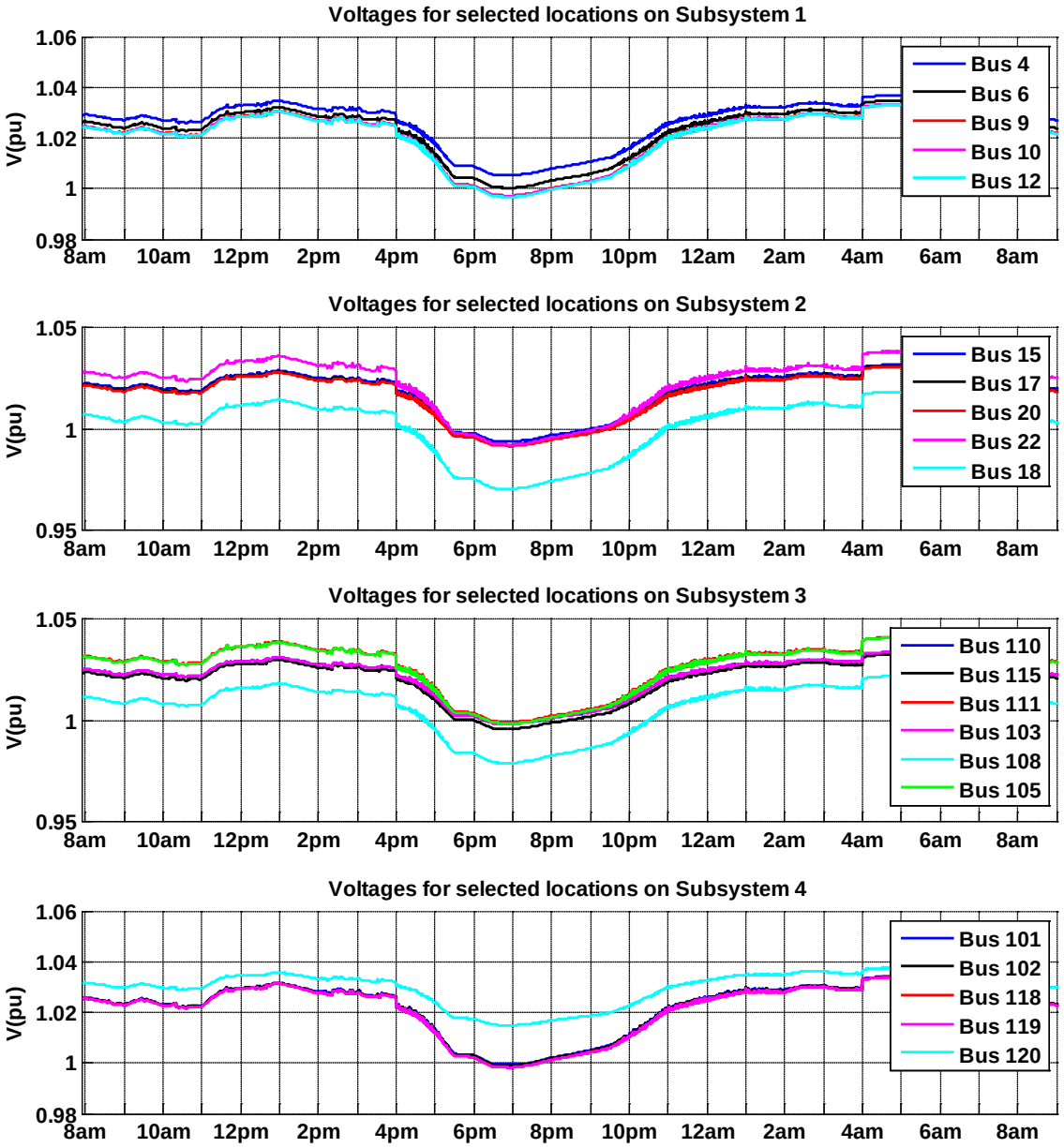

Figure 117 – Voltage at selected circuit locations for varying load and PV profile (EV Set 2, Always on)

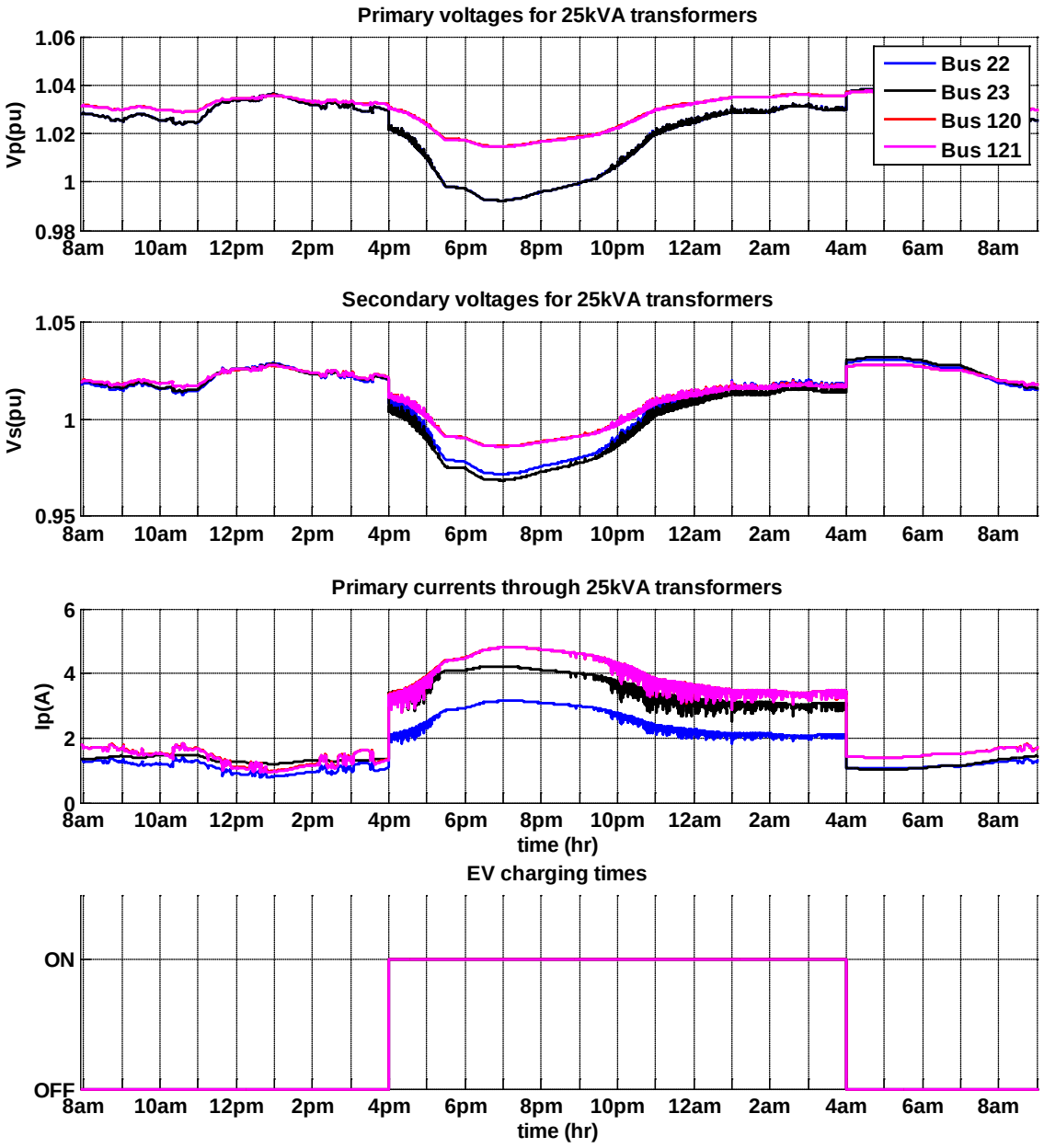

Figure 118 – Primary and secondary voltages and current at 25kVA transformers (EV Set 2, Always on)

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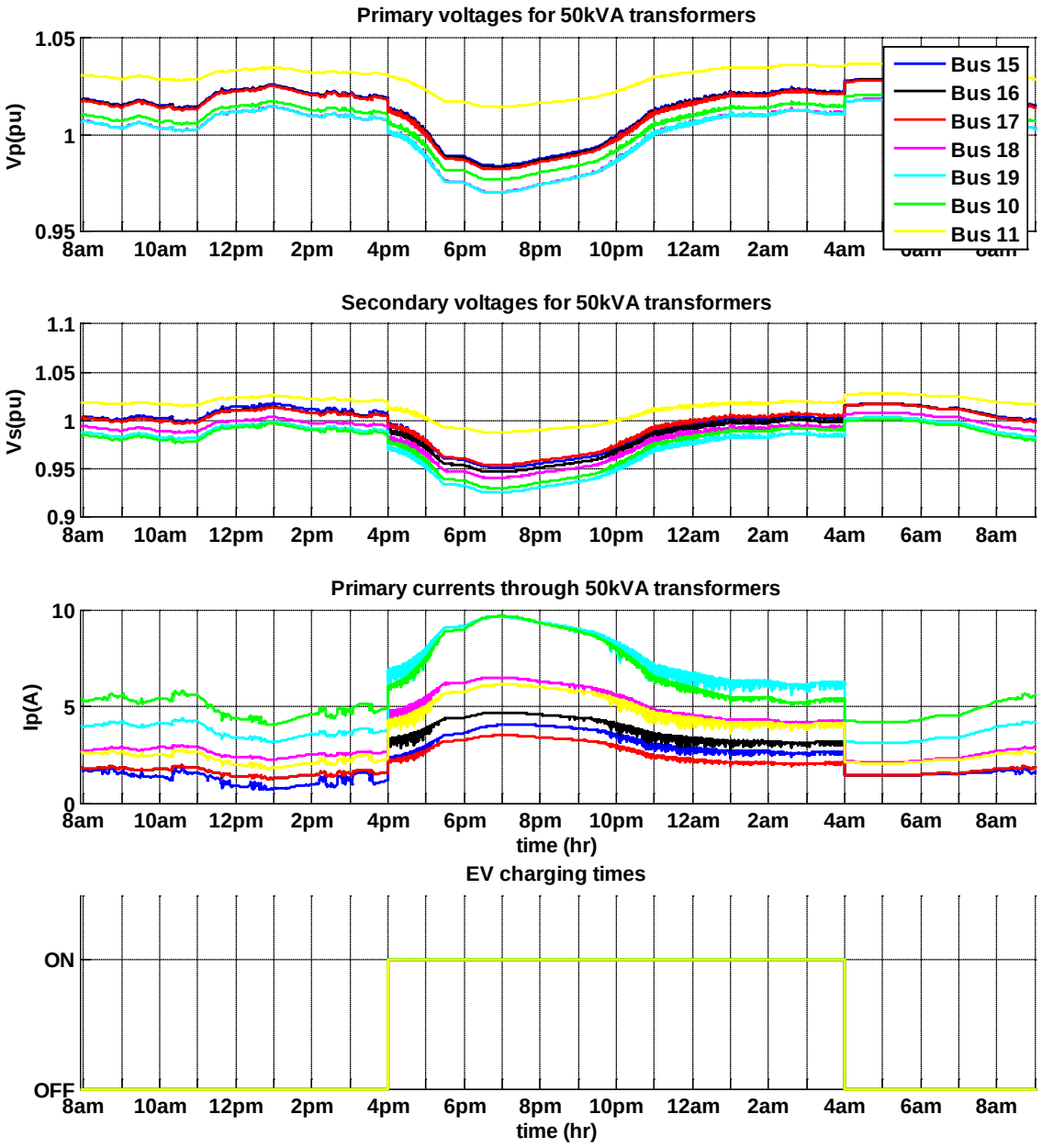

Figure 119 – Primary and secondary voltages and current at 50kVA transformers (EV Set 2, Always on)

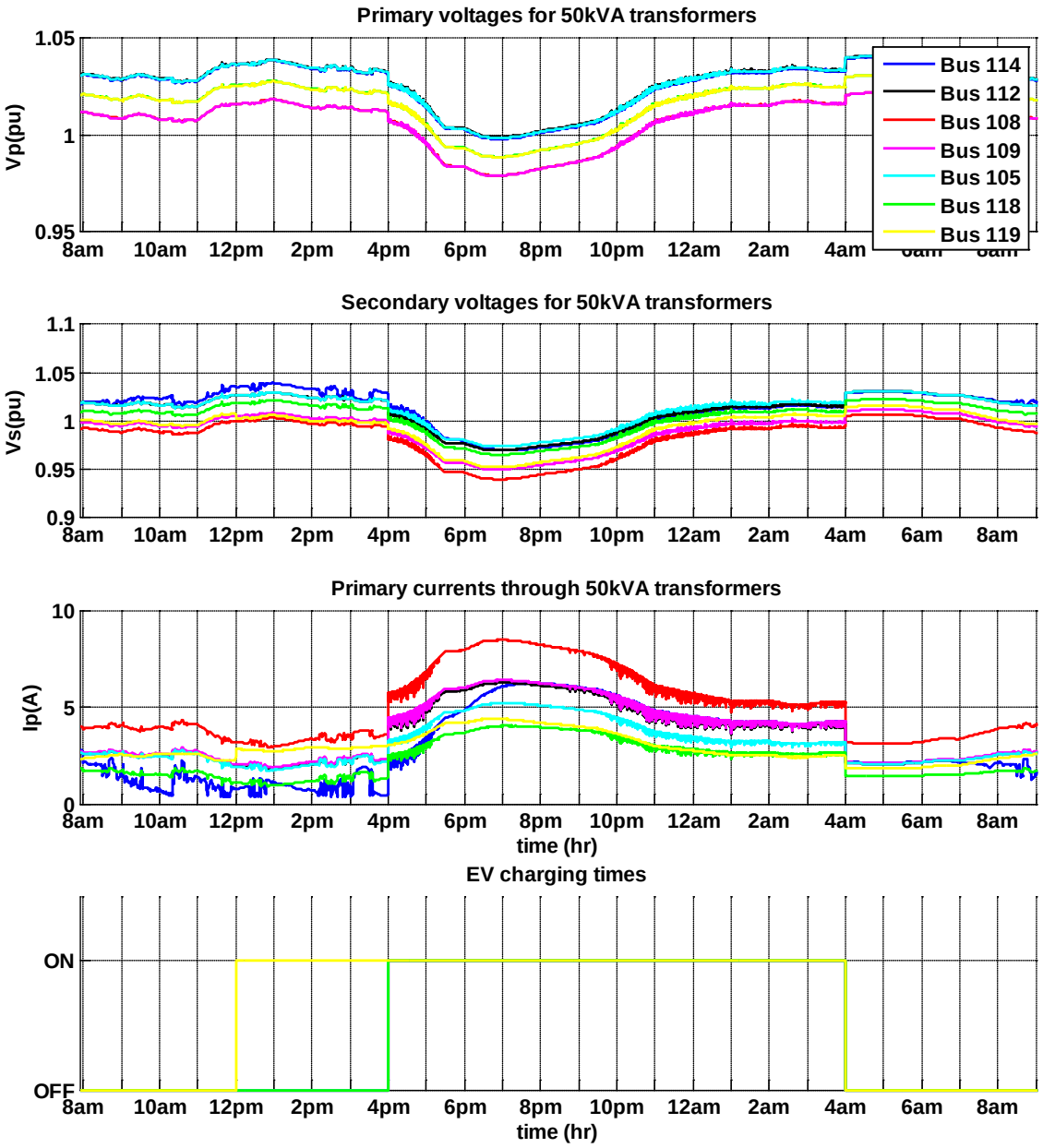

Figure 120 – Primary and secondary voltages and current at 50kVA transformers (EV Set 2, Always on)

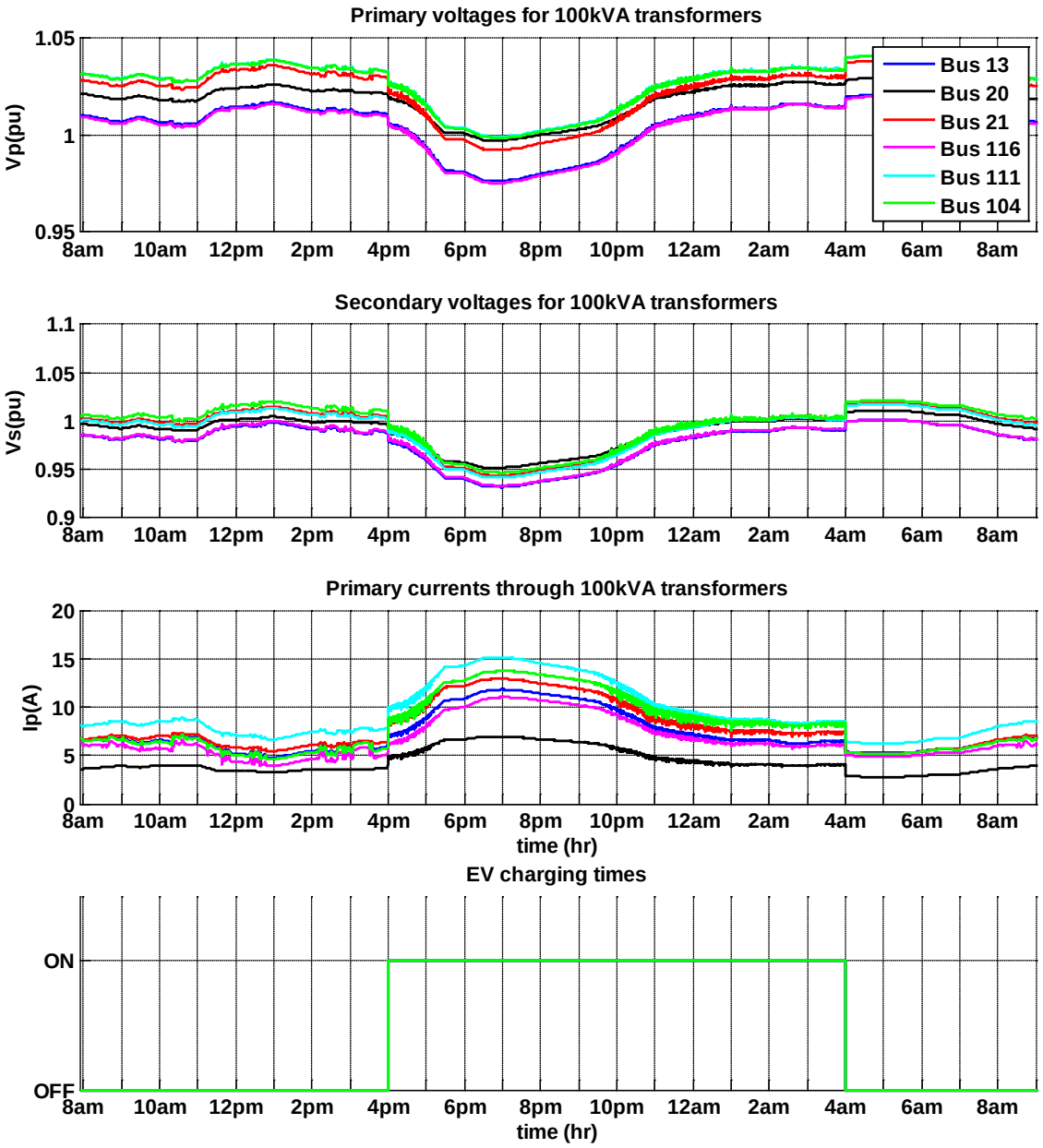

Figure 121 – Primary and secondary voltages and current at 100kVA transformers (EV Set 2, Always on)

3.11.3 EV Set 1, Uncontrolled Charging

Voltages for the entire circuit are shown in *Figure 122*. Voltages for selected locations on each subsystem are shown in *Figure 123*. Transformer voltages and currents are shown in *Figure 124* through *Figure 127*. It was observed that EV charging had a large effect on primary transformer current flow, but only a minor effect on the secondary transformer voltage. EV charging had less effect on the primary circuit voltages.

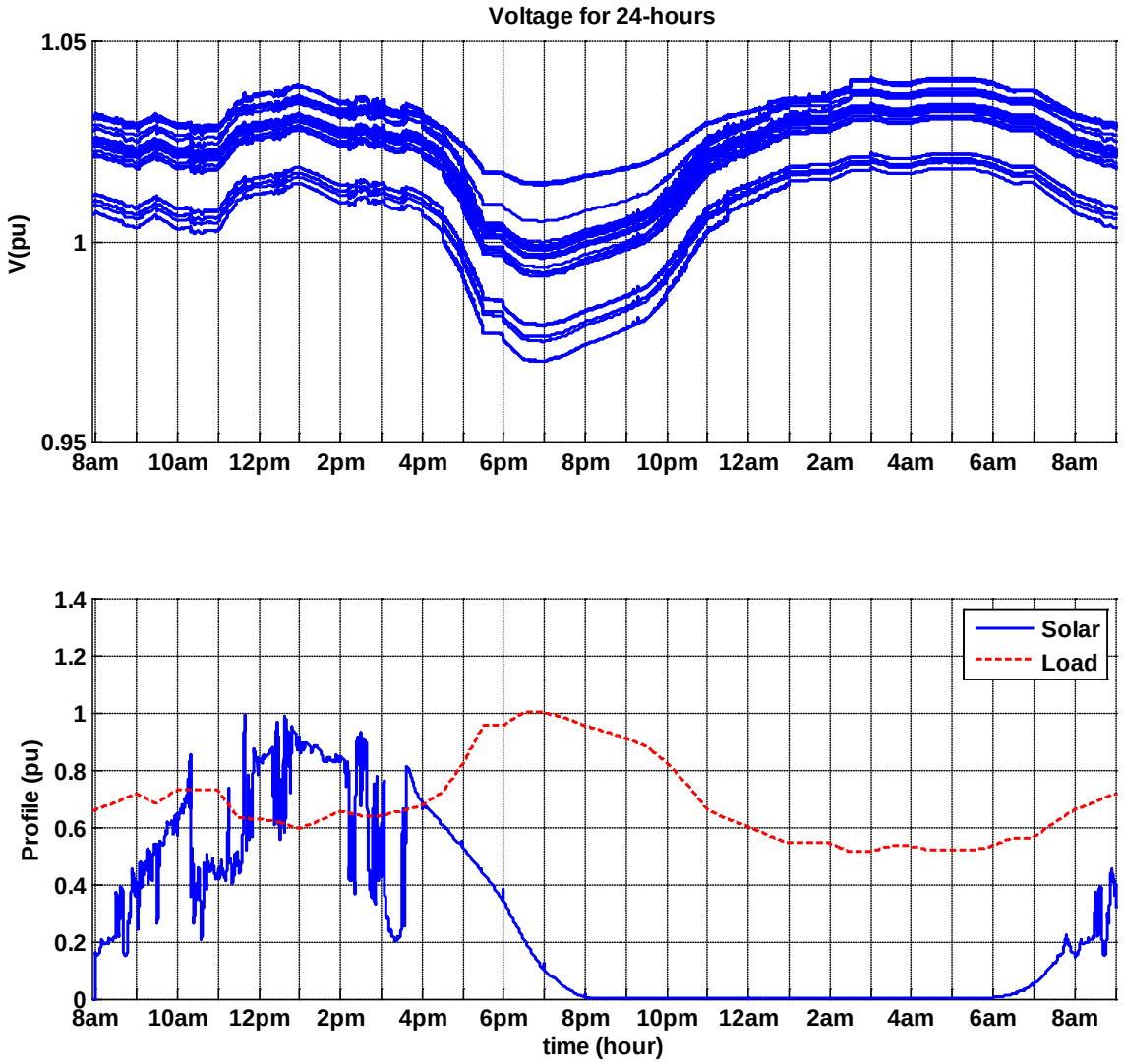

Figure 122 – Voltage at all circuit locations for varying load and PV profile (EV Set 1, Uncontrolled charging)

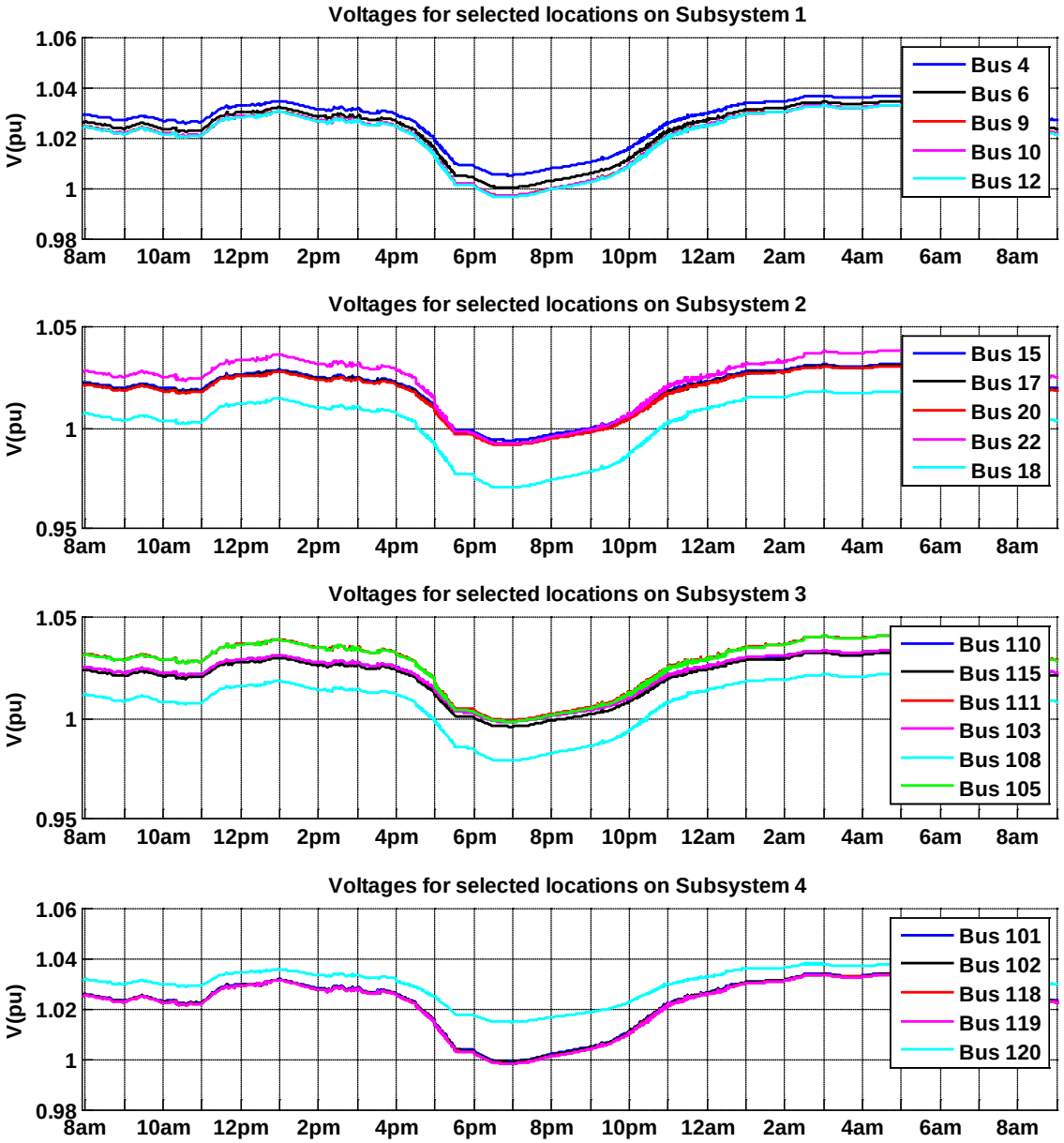

Figure 123 – Voltage at selected circuit locations for varying load and PV profile (EV Set 1, Uncontrolled charging)

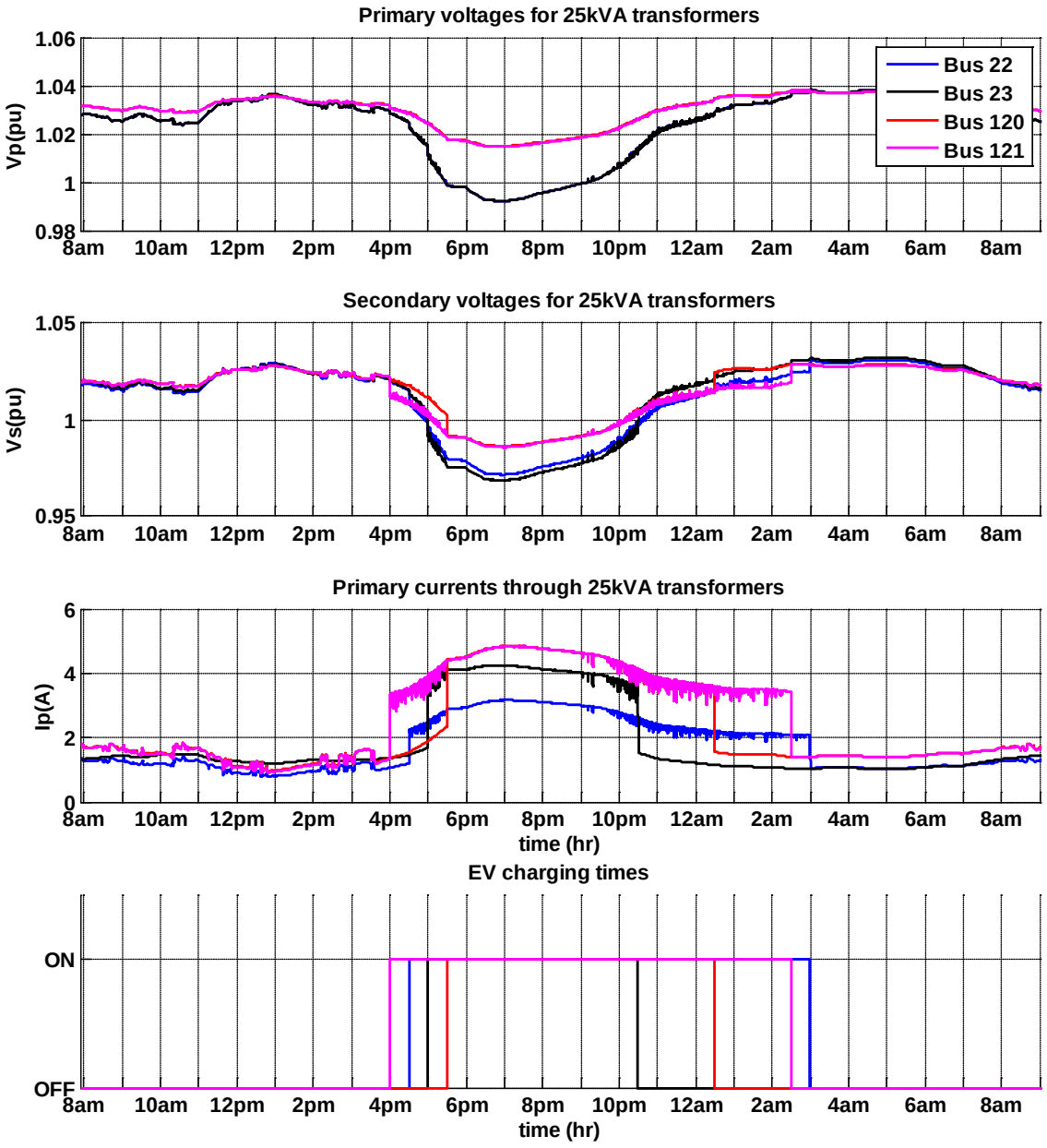

Figure 124 – Primary and secondary voltages and current at 25kVA transformers (EV Set 1, Uncontrolled charging)

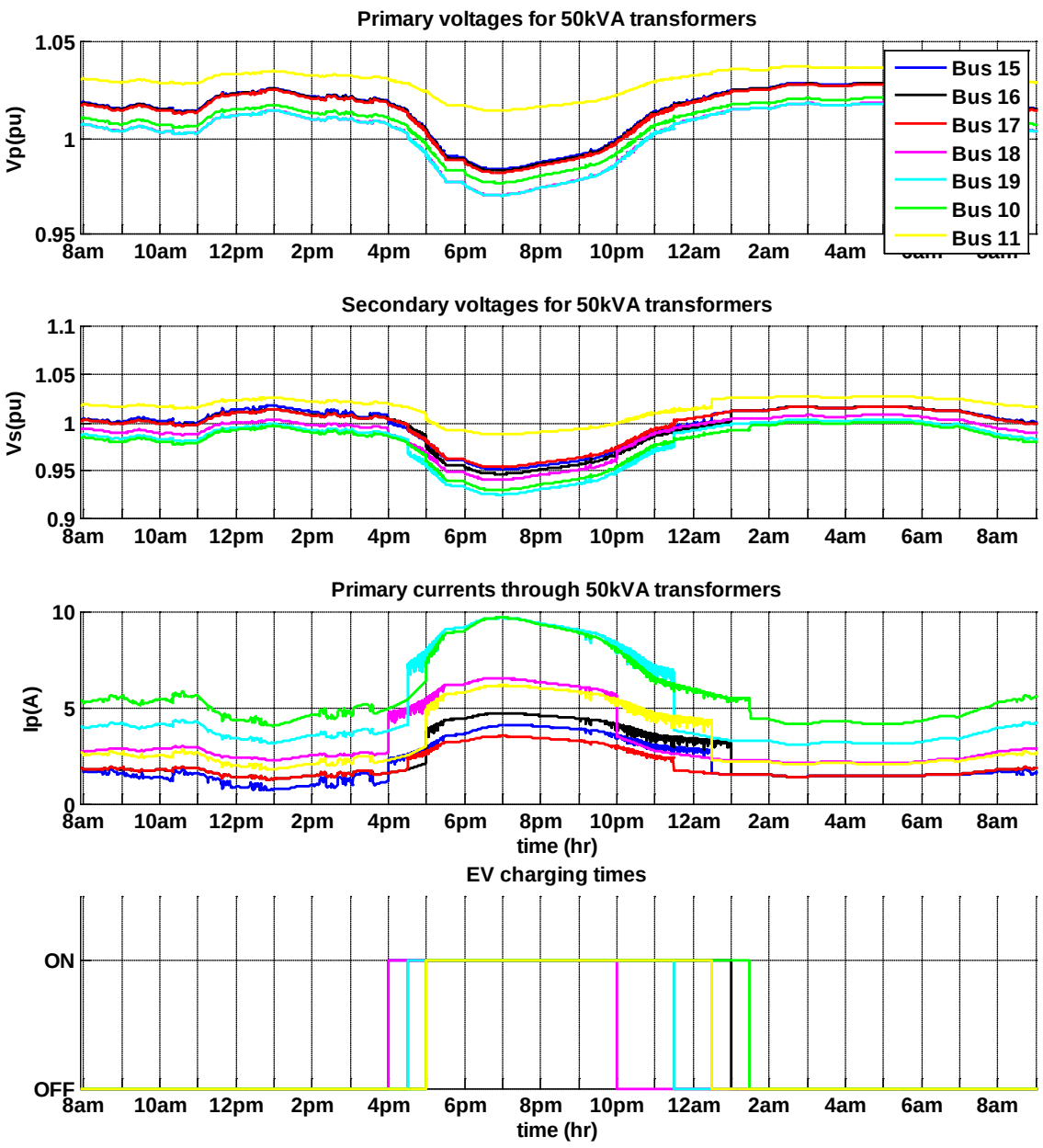

Figure 125 – Primary and secondary voltages and current at 50kVA transformers (EV Set 1, Uncontrolled charging)

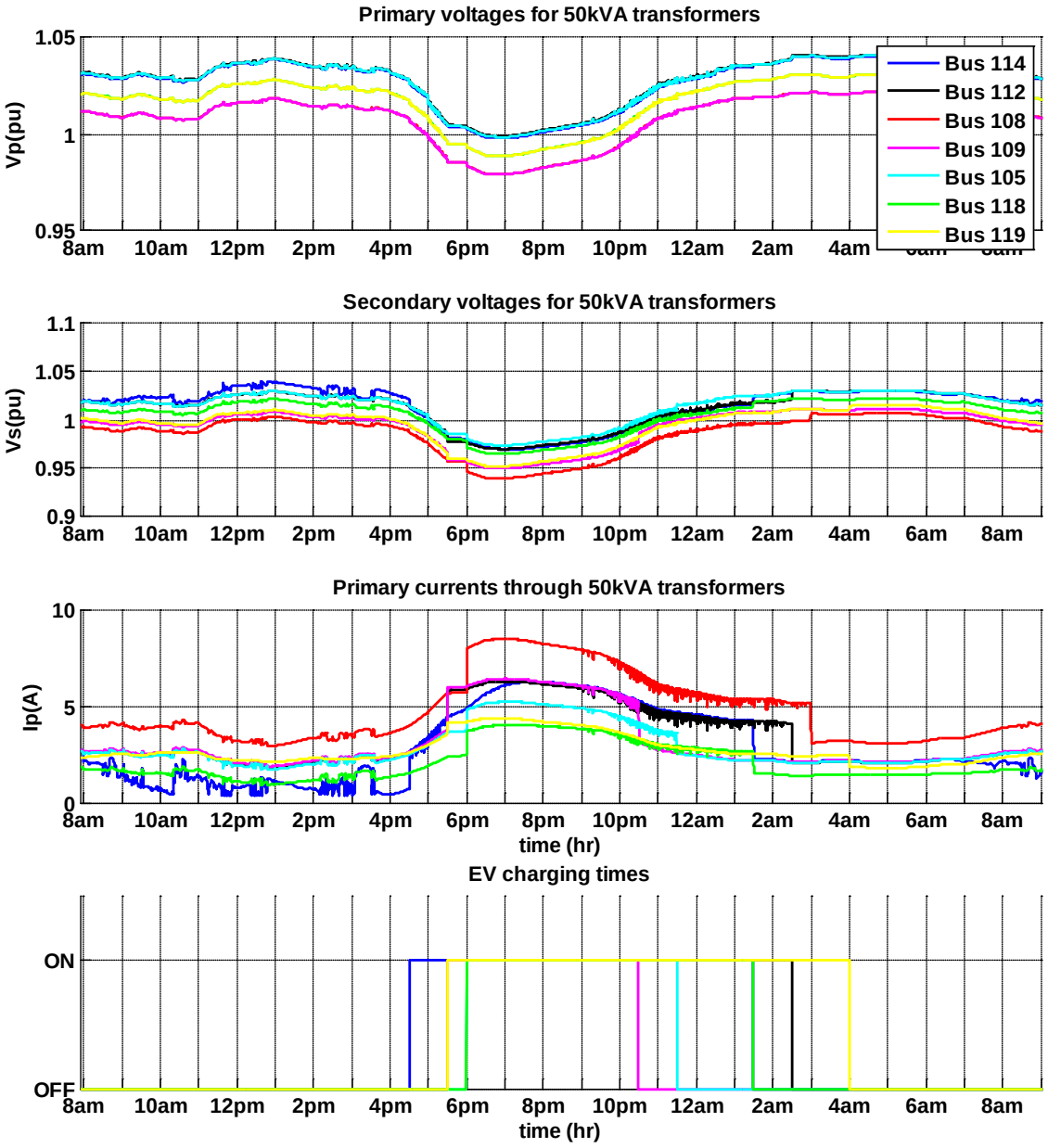

Figure 126 – Primary and secondary voltages and current at 50kVA transformers (EV Set 1, Uncontrolled charging)

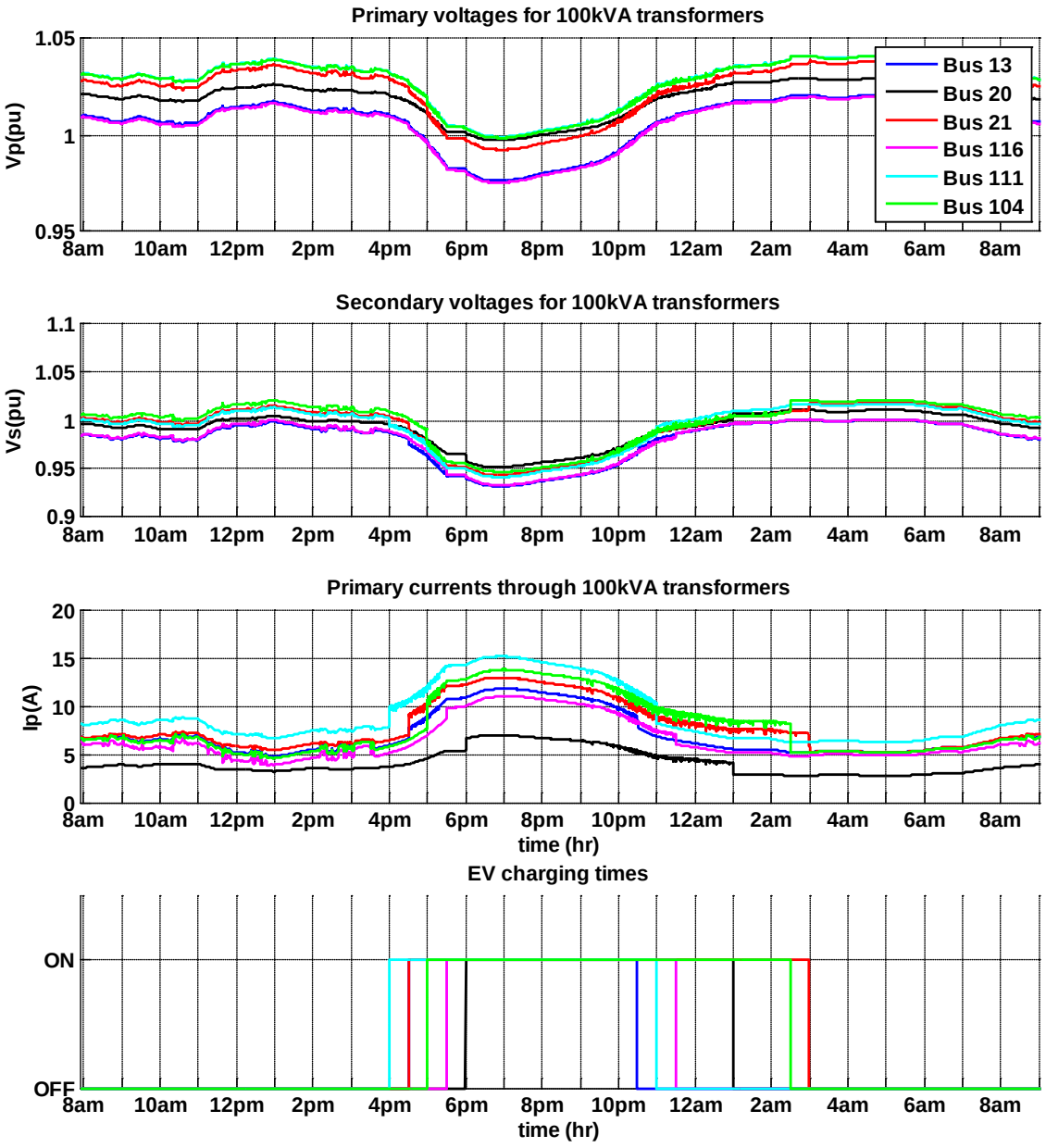

Figure 127 – Primary and secondary voltages and current at 100kVA transformers (EV Set 1, Uncontrolled charging)

3.11.4 EV Set 2, Uncontrolled Charging

Voltages for the entire circuit are shown in *Figure 128*. Voltages for selected locations on each subsystem are shown in *Figure 129*. Transformer voltages and currents are shown in *Figure 130* through *Figure 133*. It was observed that EV charging had a large effect on primary transformer current flow and the secondary transformer voltages. The voltage effect was mainly because EV charging occurred in the early evening time-frame where the system load was high and voltage was already closer to the lower bandwidth. In some cases, the loading had doubled. Additional loading reduced the voltage further. EV charging had less effect on the circuit voltage.

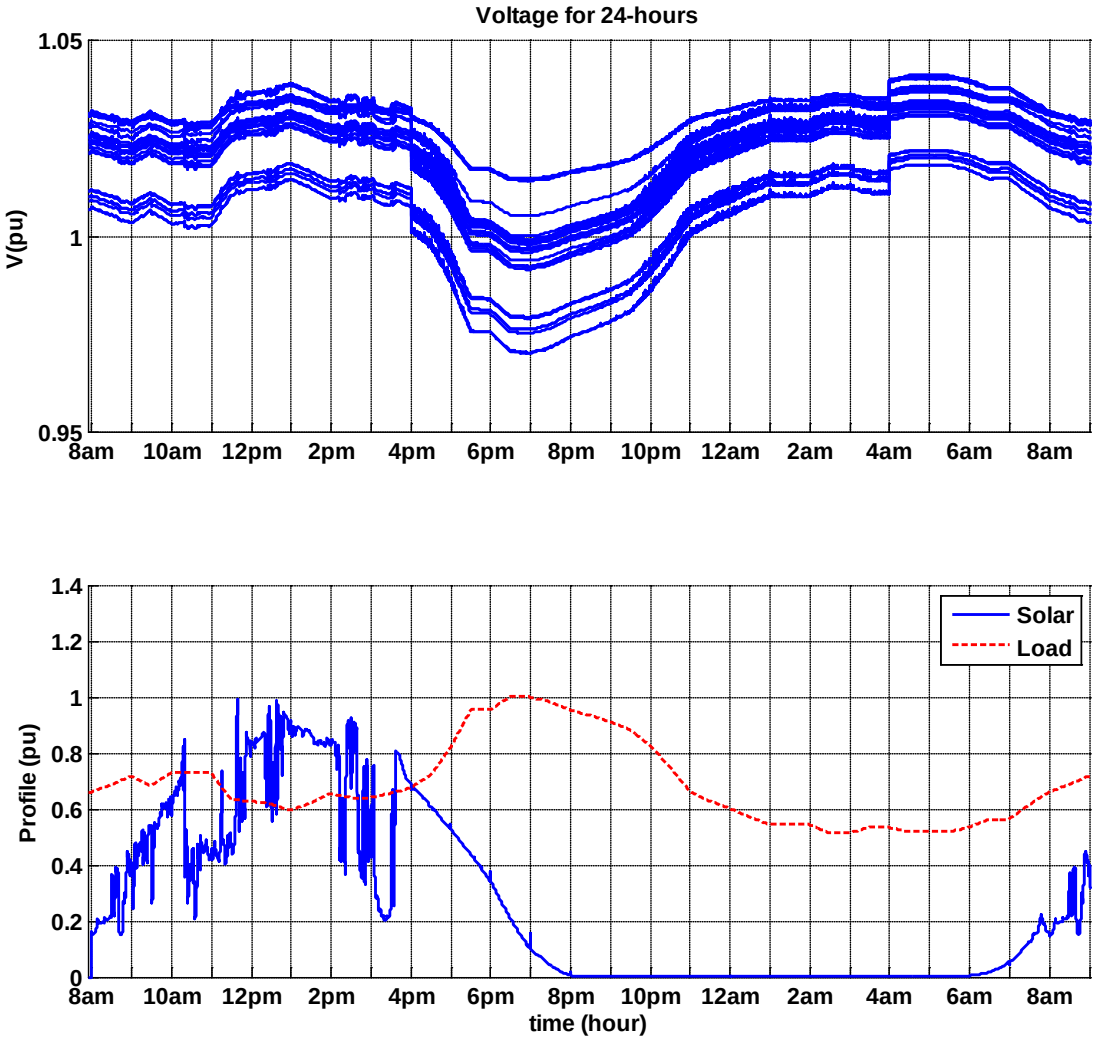

Figure 128 – Voltage at all circuit locations for varying load and PV profile (EV Set 2, Uncontrolled charging)

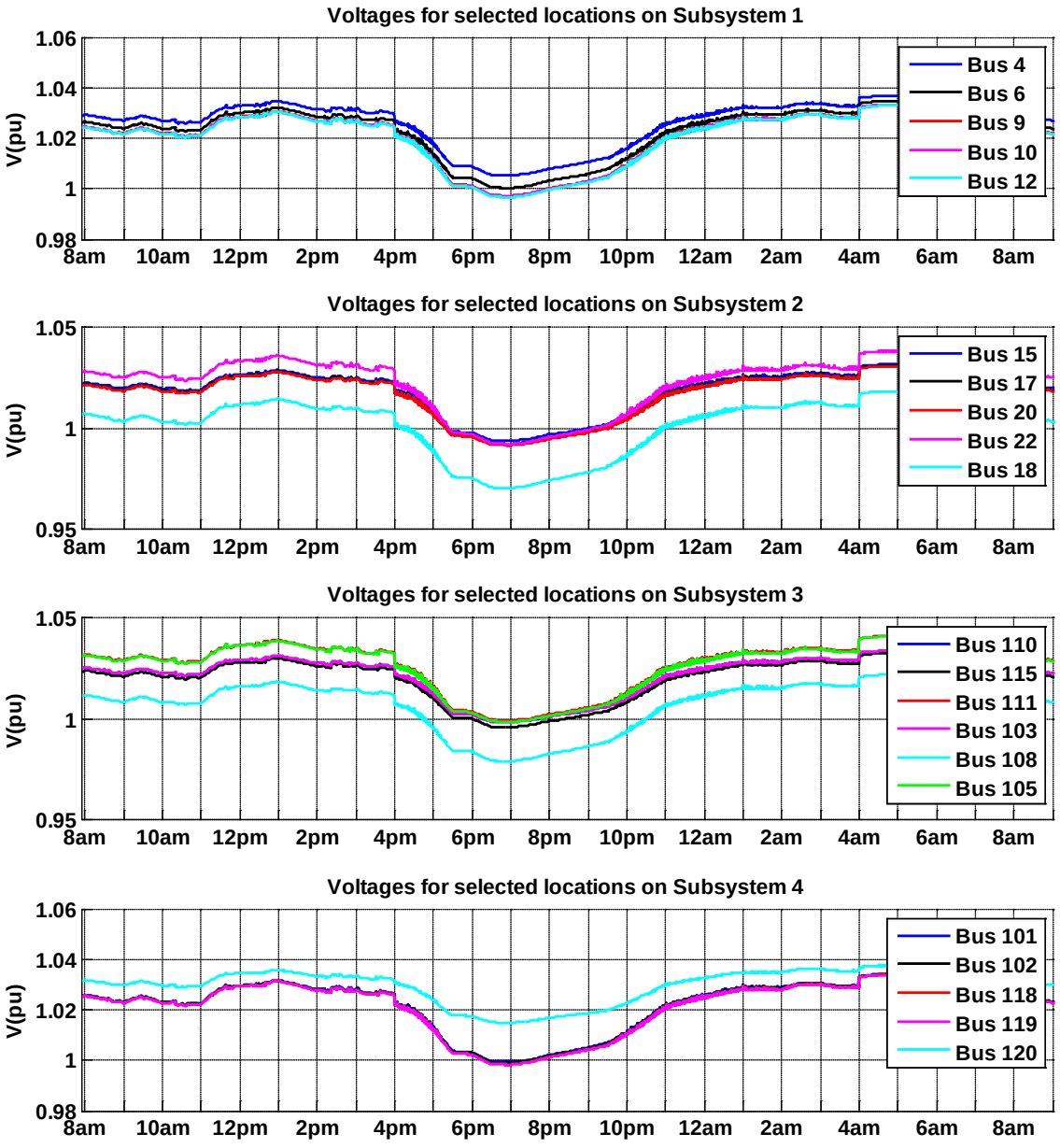

Figure 129 – Voltage at selected circuit locations for varying load and PV profile (EV Set 2, Uncontrolled charging)

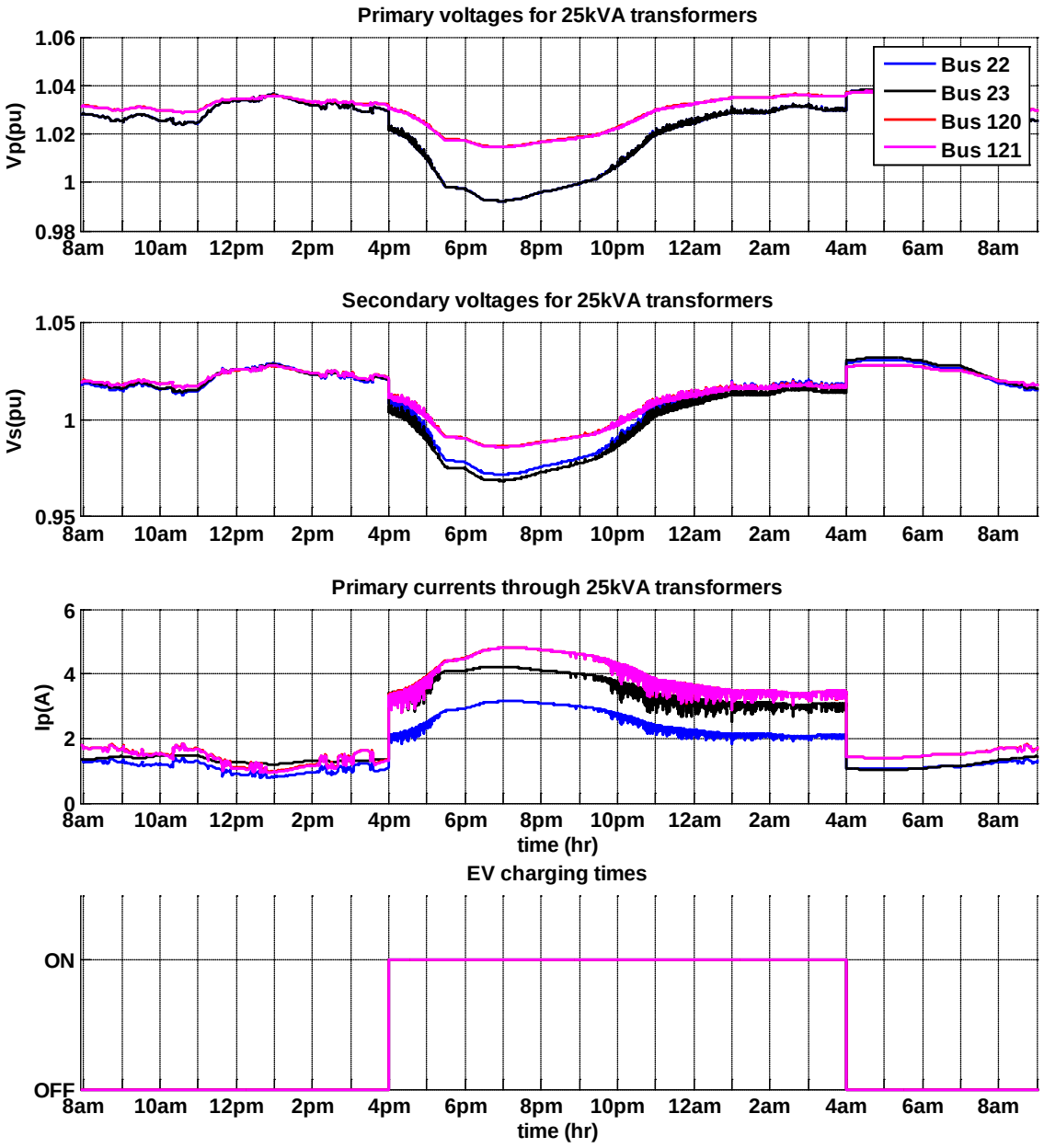

Figure 130 – Primary and secondary voltages and current at 25kVA transformers (EV Set 2, Uncontrolled charging)

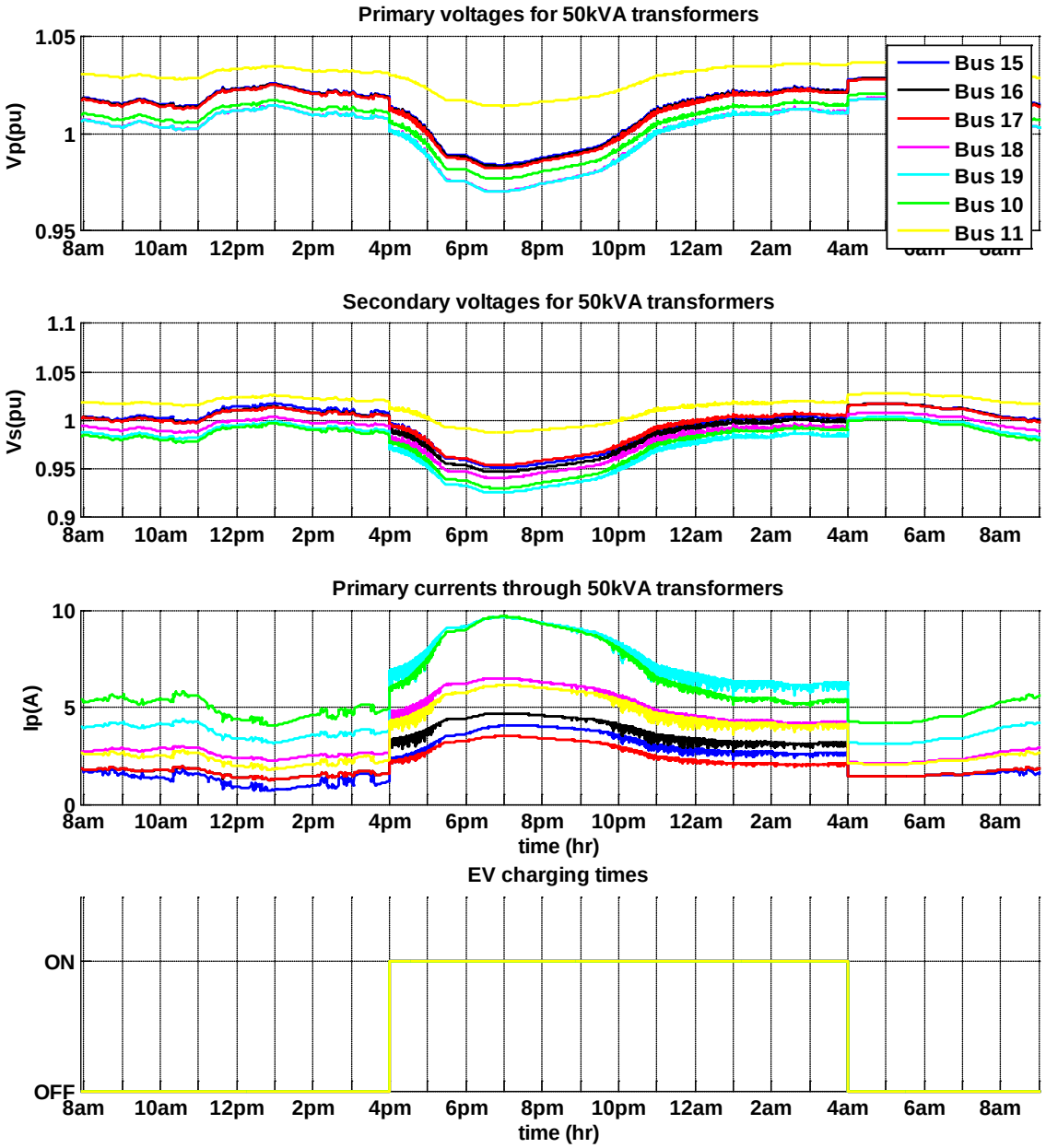

Figure 131 – Primary and secondary voltages and current at 50kVA transformers (EV Set 2, Uncontrolled charging)

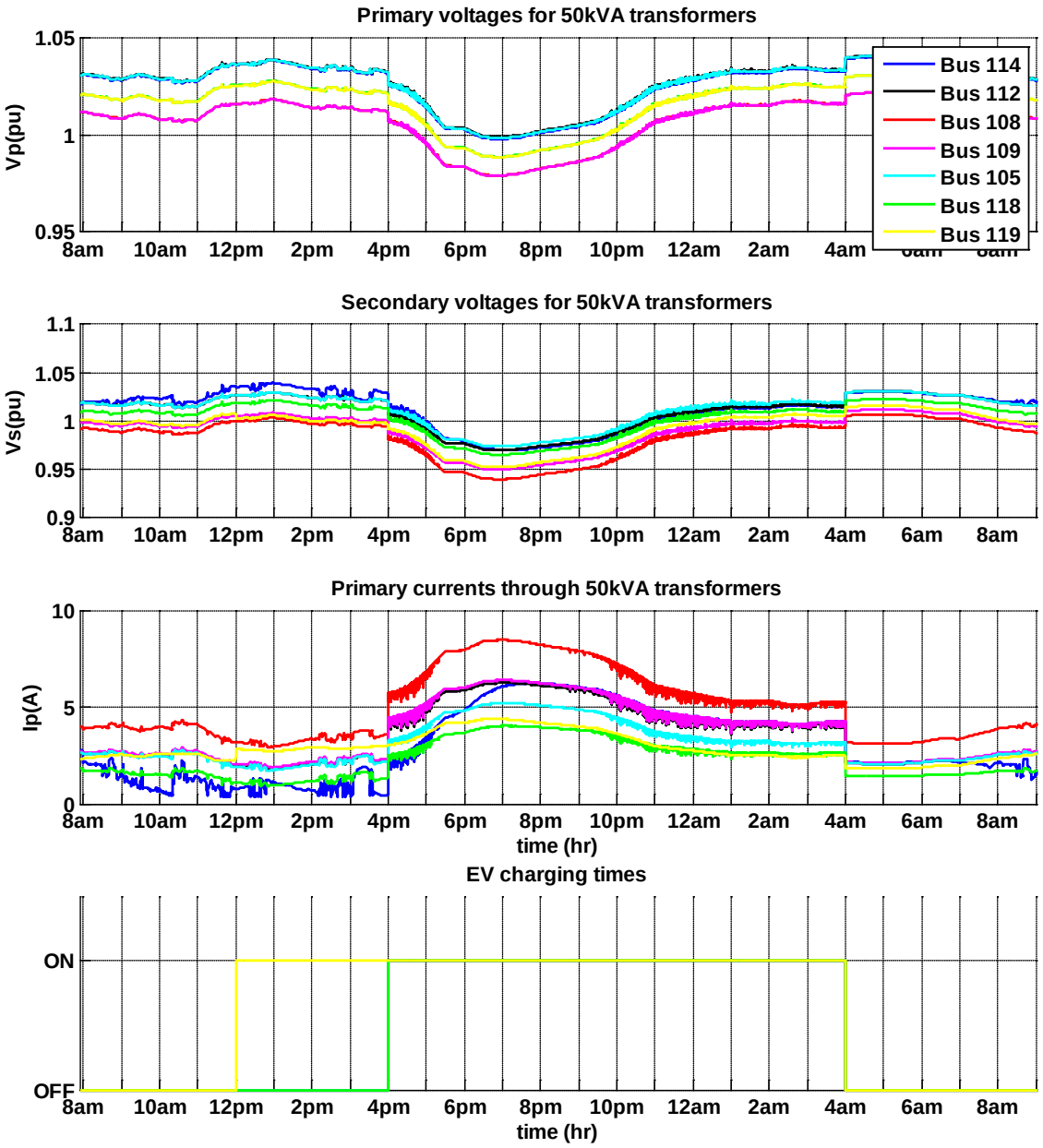

Figure 132 – Primary and secondary voltages and current at 50kVA transformers (EV Set 2, Uncontrolled charging)

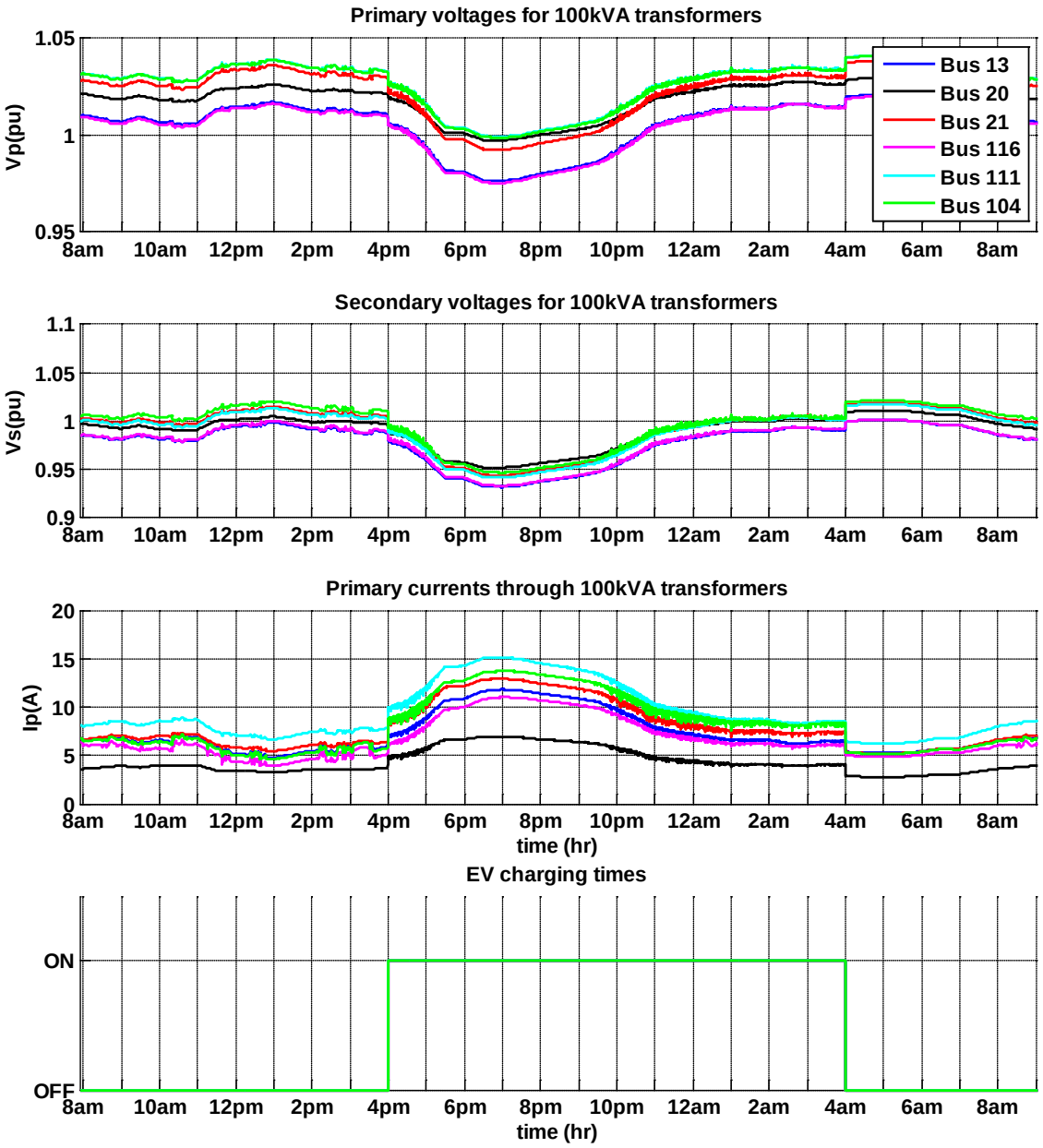

Figure 133 – Primary and secondary voltages and current at 100kVA transformers (EV Set 2, Uncontrolled charging)

3.12 *Online - Multiple EV on single transformer*

These tests involved the connection of multiple EV customers to a single transformer location on the circuit. Loads were scaled according to the full 24-hour profile, and PV generation was disabled. Two locations were selected for the connection of the transformer, representing a 25kVA and 50kVA transformer. Start and end charging times were randomly selected for each individual EV customer according to the limits defined by the uncontrolled charging time. Size and charging details are shown in *Table 11*.

Table 11 – EV size and charging times parameters

Transformer and EV Parameters						
Bus #	Transformer Rated kVA	Connection	EV	EV size kW	Uncontrolled Charging Start	Uncontrolled Charging End
120	25	C	120[1]	5.8	17:30	00:30
			120[2]	5.8	16:30	22:30
109	50	A	109[1]	6.8	17:30	22:30
			109[2]	6.8	16:00	23:00
			109[3]	9.8	16:30	02:30
			109[4]	3.5	18:00	01:30
			109[5]	3.5	17:00	01:30

3.12.1 Bus 120, Uncontrolled charging

The primary circuit voltage, transformer voltages, and transformer currents are shown in *Figure 134*. The effect of the staggered charging times of each EV customer is seen in the step decrease of secondary transformer voltage, and the step increase of transformer current. The transformer loading had tripled in some cases. The charging of EV customers had a large effect on transformer current, and minimal effect on secondary transformer voltage. There was less effect on the primary circuit voltage.

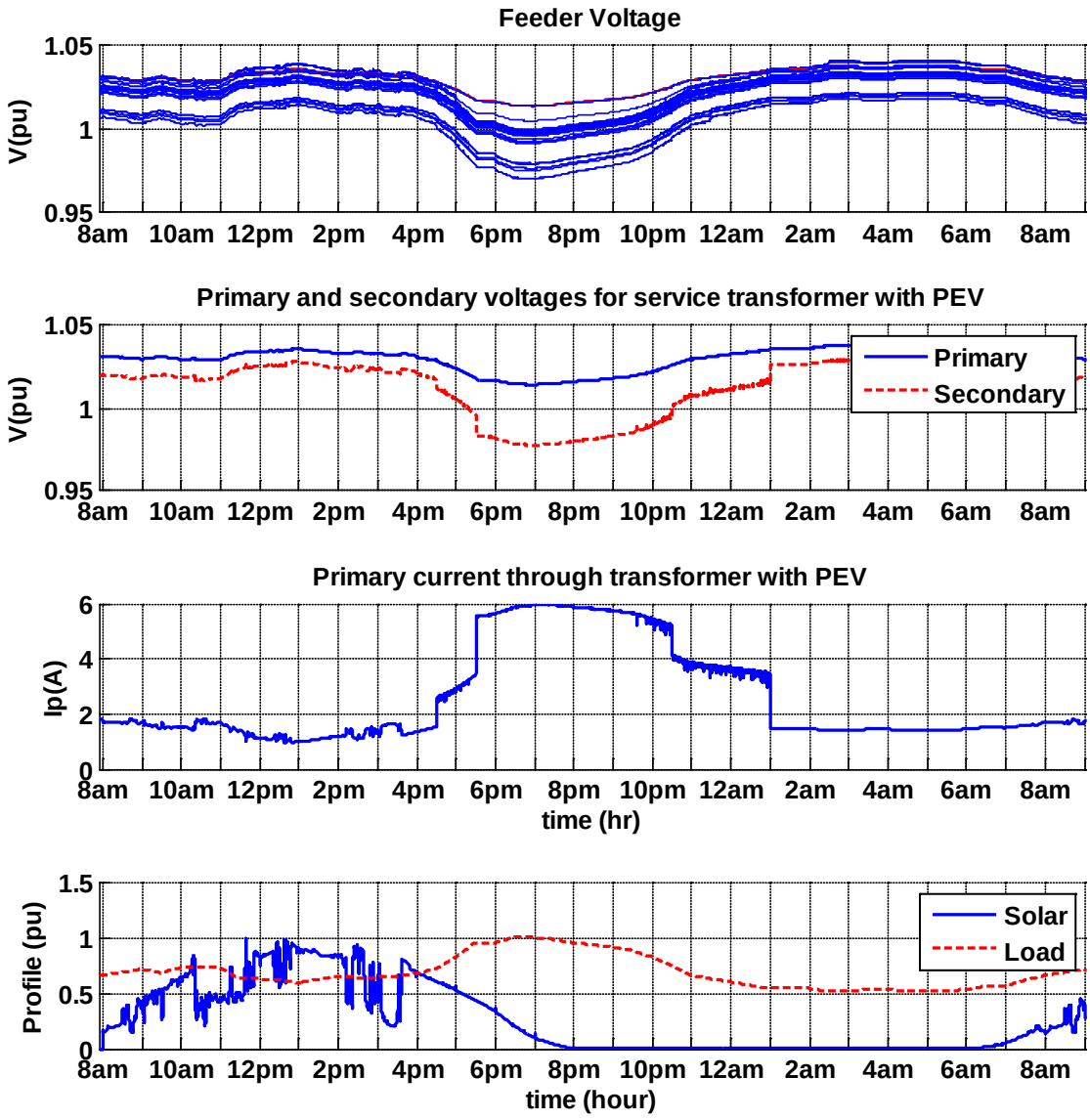

Figure 134 – Voltages and currents for multiple EV customers for single transformer at Bus 120

3.12.2 Bus 109, Uncontrolled charging

The primary circuit voltage, transformer voltages, and transformer currents are shown in *Figure 135*. The effect of the staggered charging times of each EV customer is seen in the step decrease of secondary transformer voltage, and the step increase of transformer current. The charging of EV customers had a large effect on transformer current and secondary transformer voltage, with voltage dropping to nearly 0.9pu. There was less effect on the primary circuit voltage.

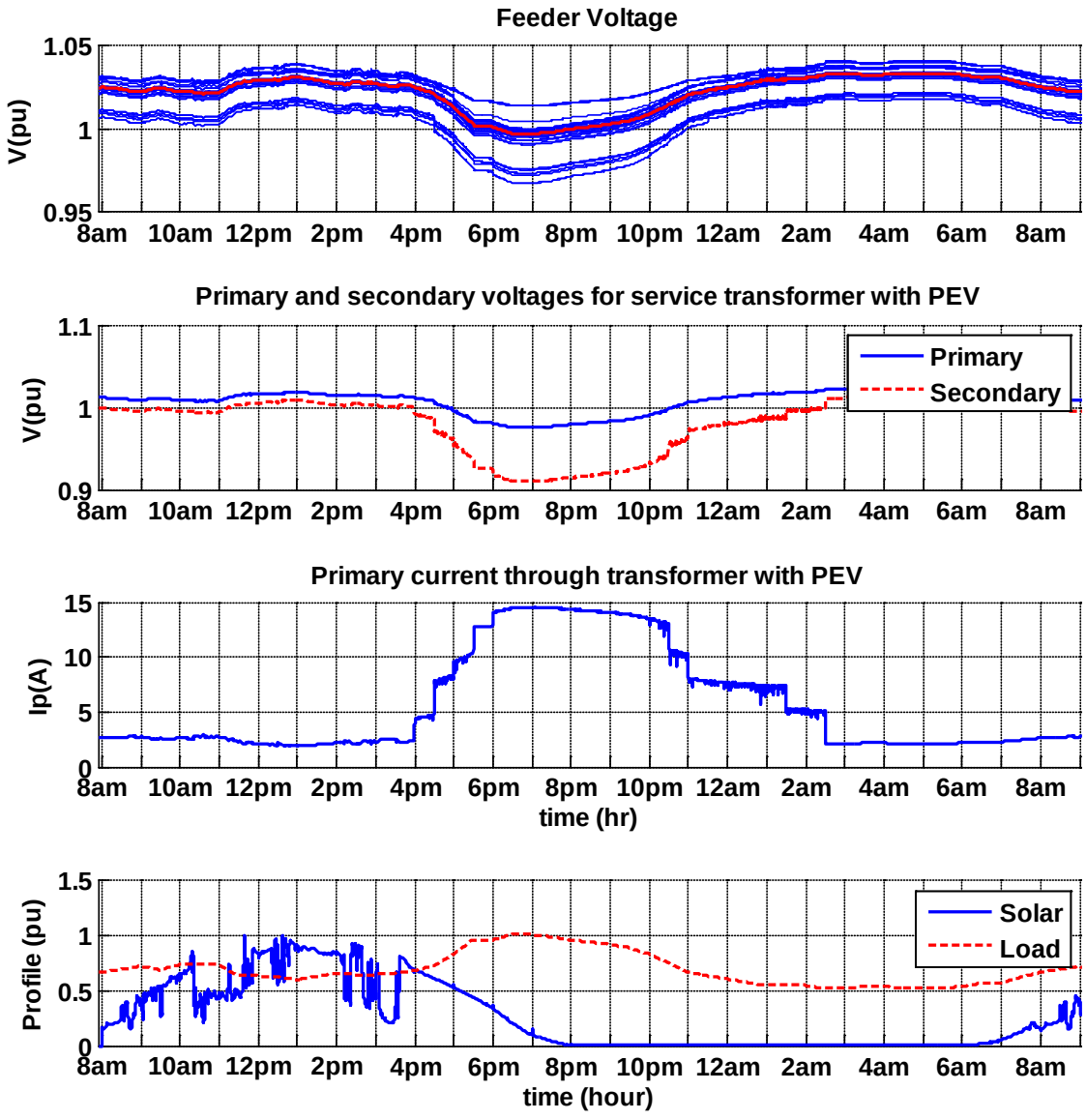

Figure 135 – Voltages and currents for multiple EV customers for single transformer at Bus 109

3.13 *Online - Full system test – large EV*

In all previous tests, the addition of EV had minimal effect on circuit and transformer primary side voltage, even when all secondary circuits had EV. The purpose of this test was to determine the size of aggregate EV at which the circuit would start to experience significant voltage issues (> 0.01pu). In this test, the EVs on all 28 secondary circuits were scaled according to existing proportions to aggregate sizes of 500kW and 1000kW.

The circuit voltage and power flow at the substation are shown in *Figure 136*. It was seen that the change in real power flow at the substation changed by less than 400kW when the EV (rated at 500kW) was active. Similar results were seen for EV aggregate size of 1000kW – the change in power flow was less than 400kW. This effect was due to the limitation of the transformer rating, which could not support more power flow to the secondary circuits.

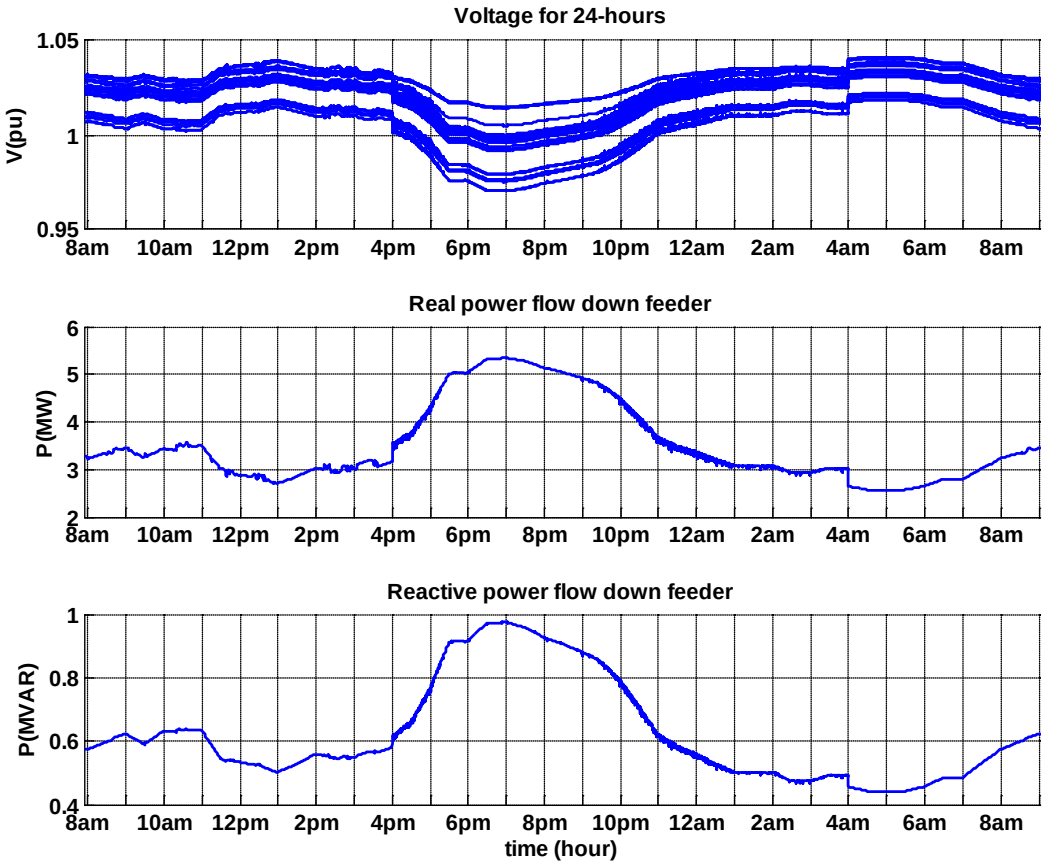

Figure 136 – Voltages and power flow for 500kW aggregate EV

3.14 *Online – DC Charger test*

Two locations were studied for the DC fast charger tests:

- One DC fast charger at Bus 5: Represented a shopping mall location, 40kW, 20 minutes active starting at 12:00pm
- One DC fast charger at Bus 118: Represented a school location, 40kW, 20 minutes active starting at 12:00pm

The DC fast chargers were supplied through existing three phase transformers that carried other loads and customers also. For both case, it was assumed that DC fast charger was used during noon time.

3.14.1 DC charger at Bus 5

The primary circuit voltage, secondary transformer voltage and currents, and real and reactive power flows into the EV charger are shown in *Figure 137*. It was seen that the effect of the EV on both primary and secondary voltages was insignificant. Bus 5 was relatively close to the substation, introducing a good candidate for deployment of DC fast chargers without adverse impact on the circuit.

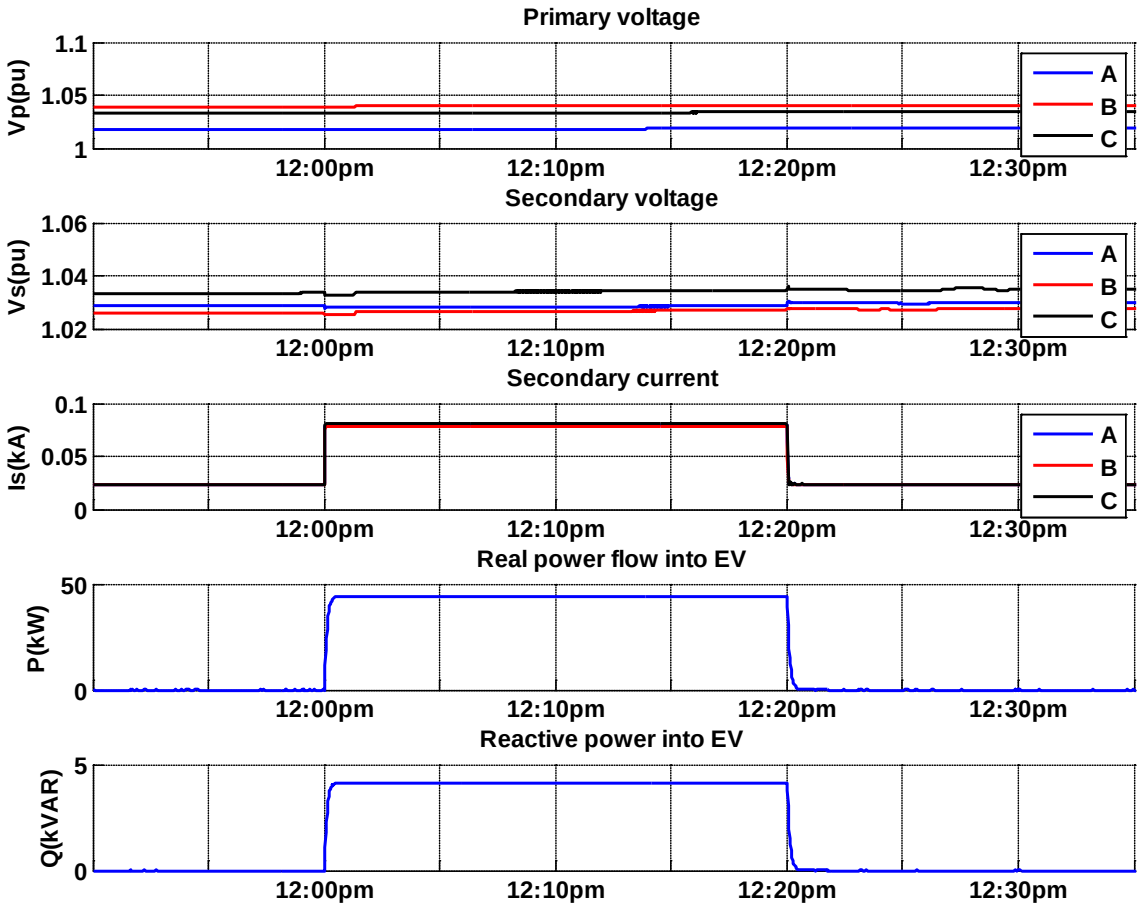

Figure 137 – Voltages, currents and power flow for DC EV charger at Bus 5

3.14.1 DC fast charger at Bus 118

The primary circuit voltage, secondary transformer voltage and currents, and real and reactive power flows into the EV charger are shown in *Figure 138*. It was seen that the effect of the EV charging on both primary and secondary voltages was insignificant.

Although this location was further away from the substation, the system was strong and impact on the voltages was negligible.

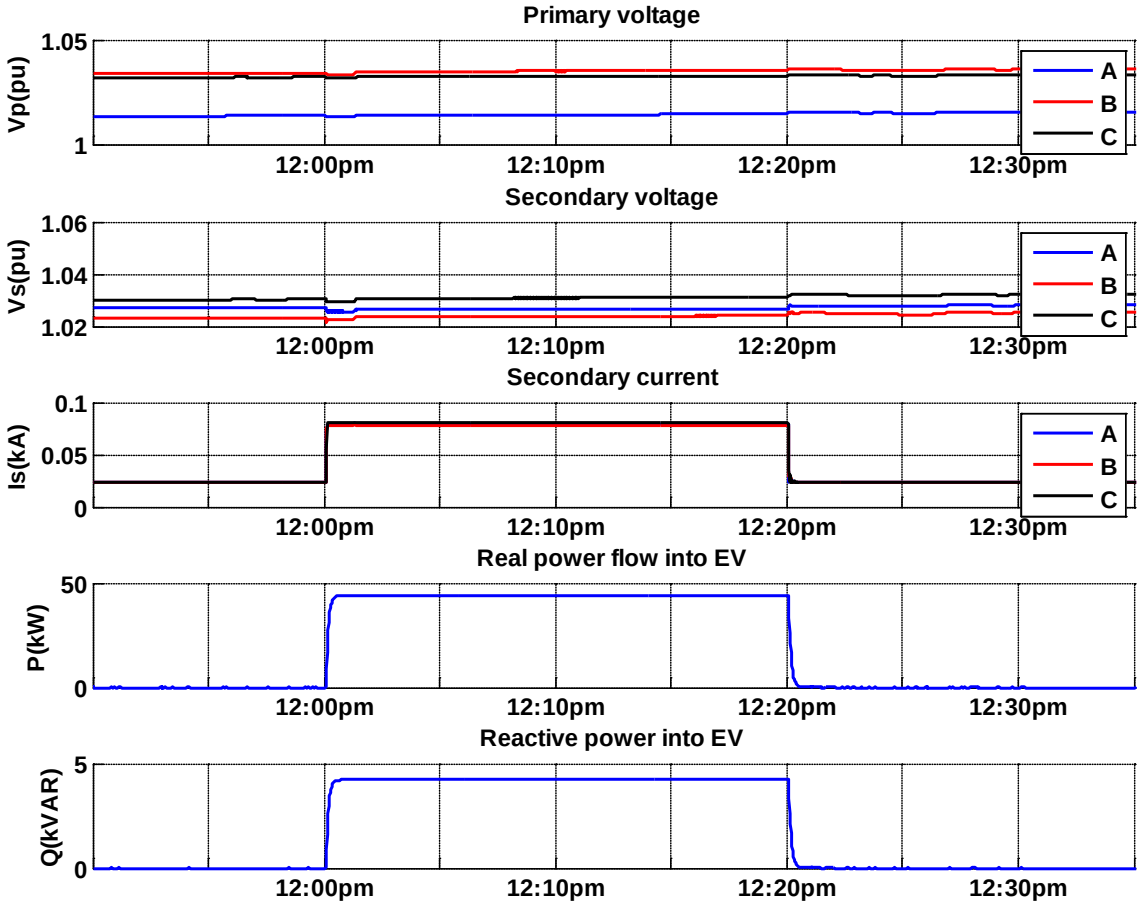

Figure 138 – Voltages, currents and power flow for DC EV charger at Bus 118

In summary, proposed locations were generally good candidates for deployment of DC fast chargers, with no expected impact on the voltages and/or operation of the circuit.

4 Smart Inverter Testing with PEV Simulator

During the design of the DC fast charger simulator (PEV rack 2), it was noted that this simulator could also be utilized for testing Smart Inverter capabilities with RTDS through power hardware in the loop simulation. PEV rack 2 included two transformer-less (TL) three phase 480 V inverters. The inverters offered several control features through communication channels with the inverters, such as:

- Dynamic power factor adjustment
- Reactive power and voltage control
- Power curtailment

The remote control using communications with the two inverters were performed through a cluster controller as shown in Figure 139. The cluster controller used a proprietary protocol to communicate with the downstream inverters, but a Modbus protocol to communicate with outside world for receiving commands and transferring measurements and status.

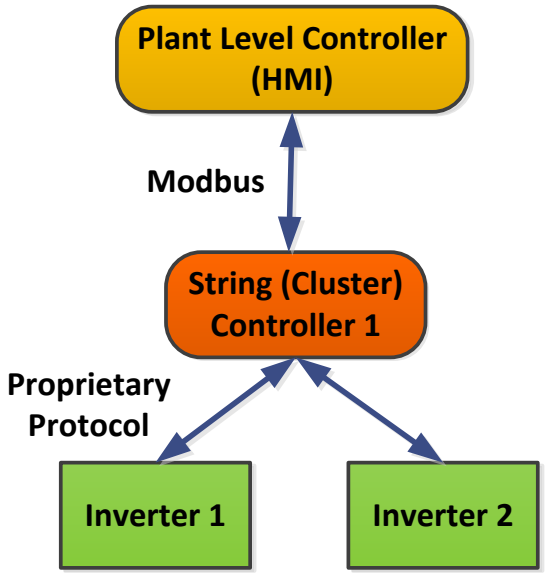

Figure 139 - Communication architecture for the Smart Inverter tests

PEV simulator rack 2 used the above mentioned communication structure to exchange set-points and data measurements with the two inverters. A use control page was added to the HMI design which allowed specifying power factors and power curtailment setpoints for the multiple inverter system (in this case, two inverters).

The HMI page for controlling the inverters and testing smart inverter features is shown in Figure 140. Customized free-control mode and Customized controlled setpoint mode were the two control options that were specifically implemented for the inverter testing. As shown, the power curtailment setpoint and power factor could be dynamically changed throughout a test. The information was communicated through the Mod-bus commands to the cluster controller in the EV simulator rack, and from there to the two inverters on the rack. Examples of data exchange with individual inverters are shown in Figure 141.

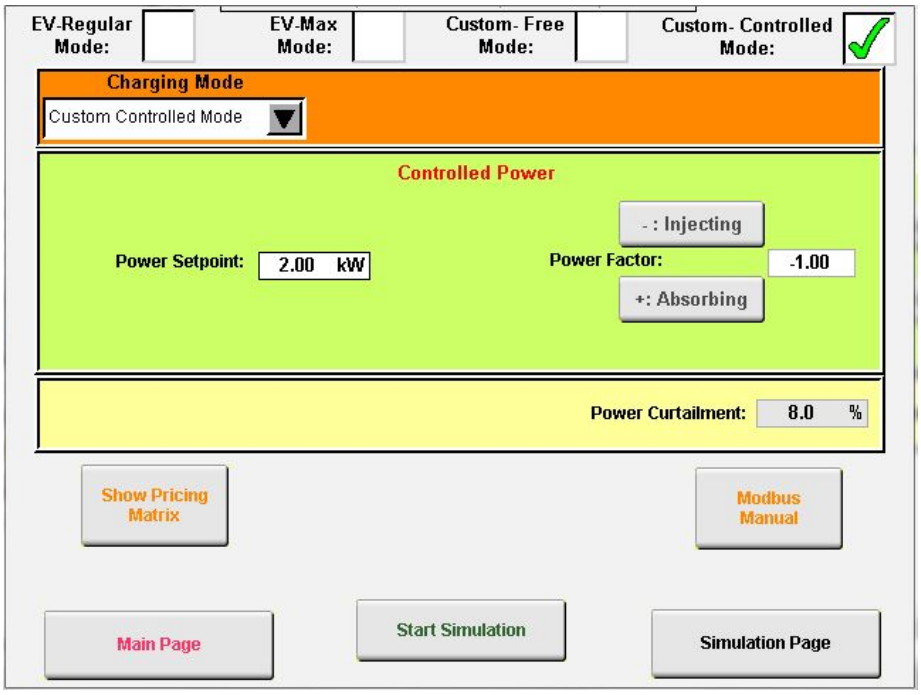

Figure 140 – HMI page for selection of control modes

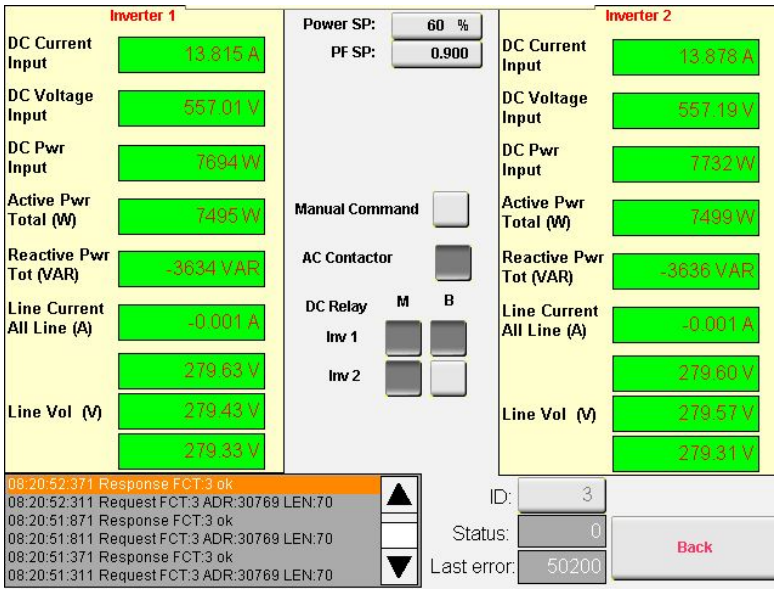

Figure 141 – Modbus communications for measurements and commands

An example of custom control simulation for the inverter with 60% curtailment and -0.9 power factor (injecting reactive power) is shown below in ***Figure 142***.

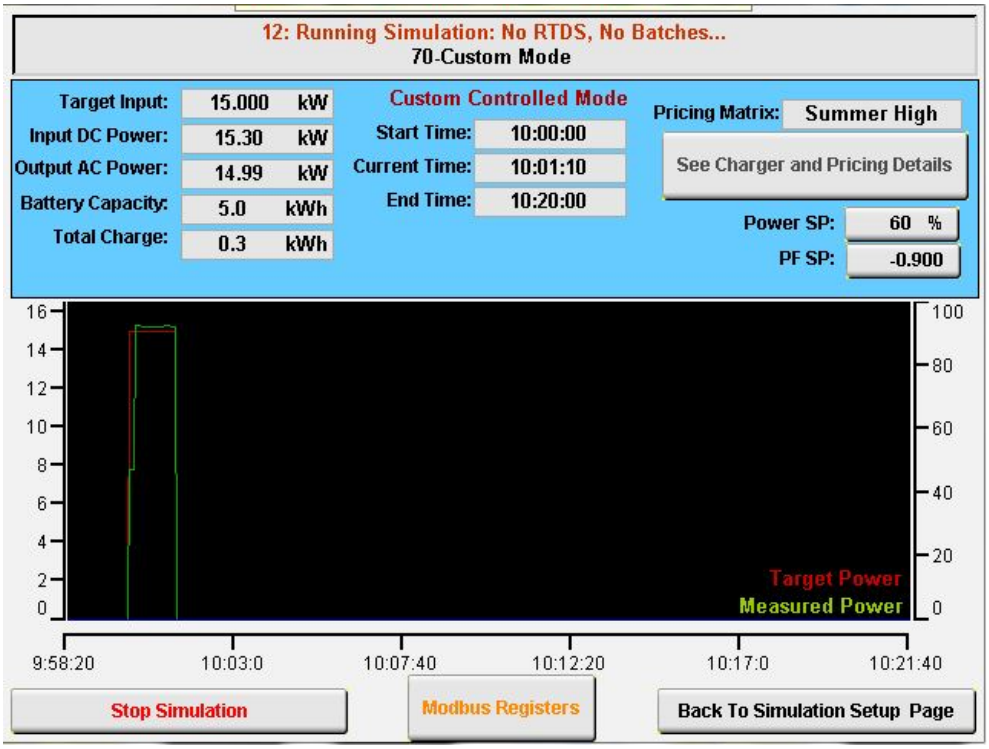

Figure 142 – Simulation page for custom control of inverters with dynamic power factor

An example of the snapshot capture for inverter currents and voltages from the tests is shown in Figure 143.

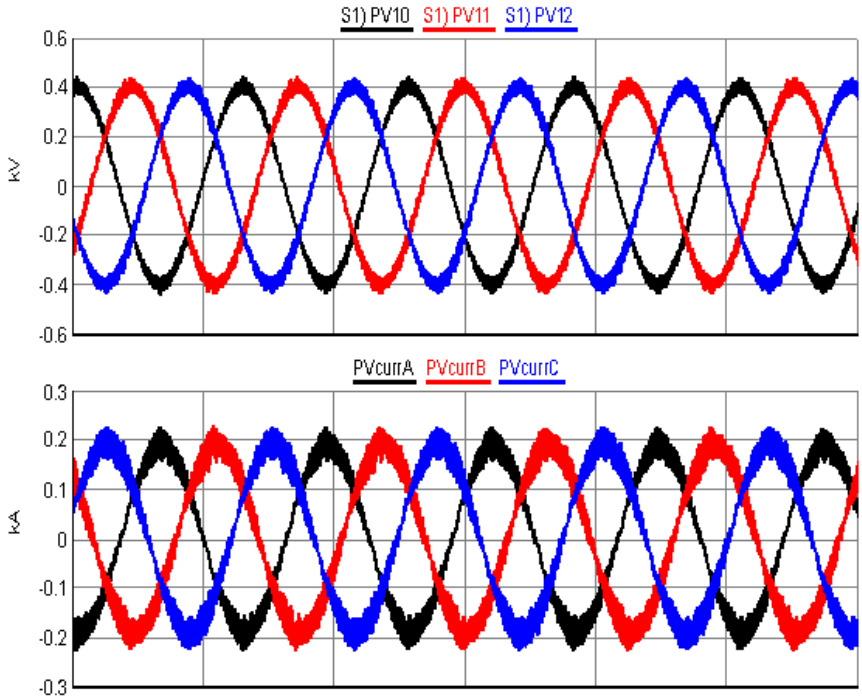

Figure 143 - Voltage and current waveforms as captured by RTDS closed loop tests

During the tests, it was noted that power curtailment had direct impact on the MPPT scheme of the inverters. The effect on the maximum power curve is shown below in ***Figure 144***. The operating point had moved away from the maximum point of power tracking and power curve.

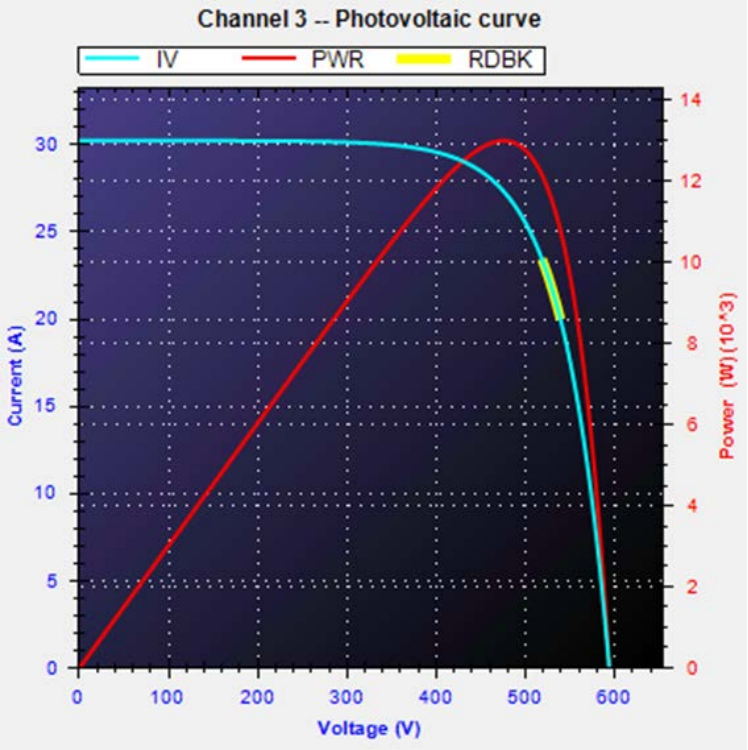

Figure 144 – Power curve of the inverters under power curtailment

Several tests were introduced and examined with the test-bed to verify the advanced features of the new generation of transformer less inverters including:

- Inverter operation at various power curtailment levels and variations in power factor
- Inverter operation with asymmetrical voltages or under unbalance loading conditions operation
- Fault current testing of the inverter and effect of controls and protections on the dynamic response of the inverter
- Performance during accidental islanding and TOV effect

As an example, the current and voltage waveforms captured from applying a single line to ground fault at the terminal of the inverters are shown in the ***Figure 145*** below. As was observed, the inverters in this case had been able to ride through the fault and did not disconnect, since the voltage drop at the point of inverter connections was not large enough.

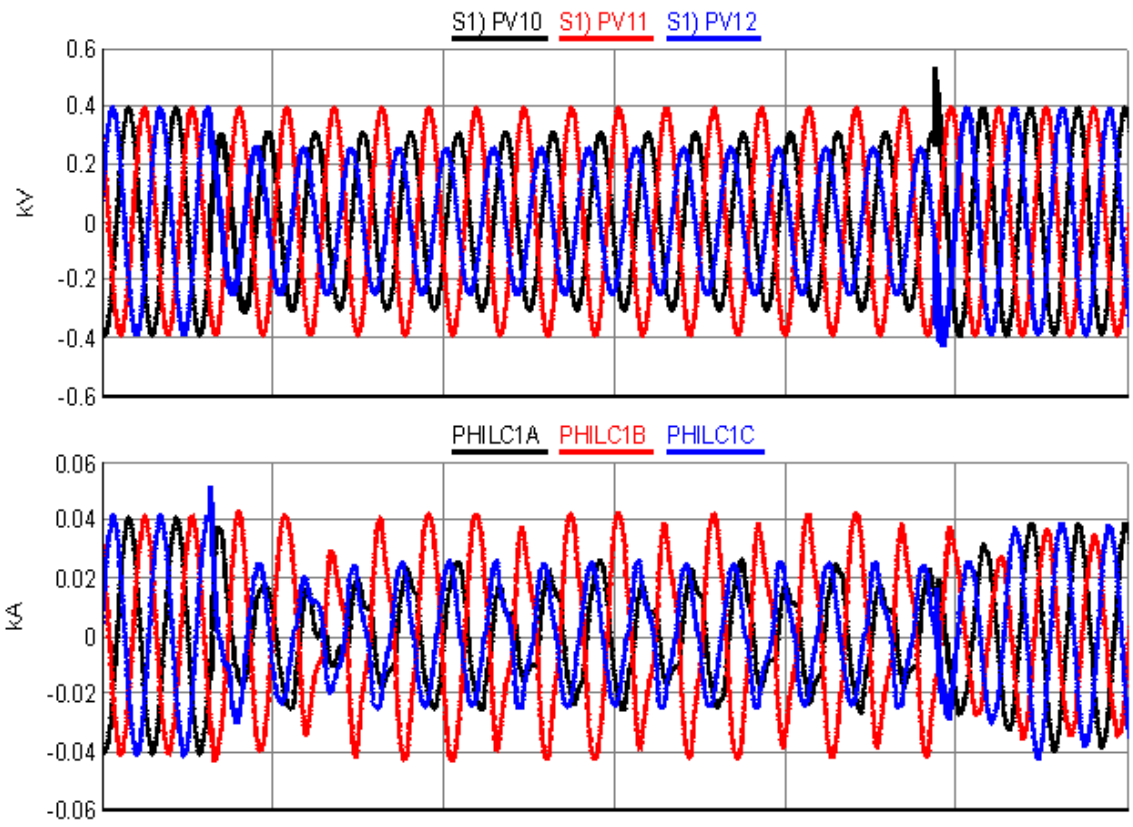

Figure 145 – Effect of single phase fault at terminal of inverters on voltages and currents

In addition, it was tested that several inverter parameters could be changed through the communications including the inverter protection settings and re-connection time delay for re-start after grid restoration. This was an advanced setting feature that was available on non-certified inverters and could be requested by utility customers to coordinate the protection settings with the utility requirements.

5 Summary and Conclusions

This report introduced testing methodology and outlined detail results of testing possible system impact of various types and sizes of EV chargers installed on a representative distribution circuit. Changes in primary and secondary voltages, as well as active and reactive power flow through service transformers were measured and reported. Overall, it was assumed that various types of EV chargers were installed and utilized by residential customers or deployed at public locations.

The representative circuit was selected through survey of the SDG&E distribution circuits that relatively had a large number of existing customers with EV chargers.

Several test scenarios were proposed and tested, including cases with:

- Single customers utilizing EV chargers
- Multiple customers in vicinity of each other using EV chargers
- Multiple customers supplied from a common service transformer using EV chargers
- All existing customers with EV chargers using their EV chargers
- All represented customers and lumped loads on the circuit using EV chargers

In addition, sizes of the EV chargers were also randomly selected and assigned to service transformers. In areas where roof-top or small commercial PV systems were also available, PV system were modeled and included in the tests and studies.

Two EV utilization scenarios were also incorporated.

- In Scenario 1 (Uncontrolled scenario): Use of EV chargers was assumed to be uncontrolled. In this scenario, an EV customer would start charging EVs as soon as they arrived at residential or small commercial locations with level 2 AC chargers. To arrive at a more realistic case, the size, start time and end time of the EV charging were randomly selected and incorporated into the test plan to represent a consistent set of test data for various tests and investigations. As a result, most EV chargers would start the charging process during the evening time.
-

- In Scenario 2 (Controlled scenarios): EV chargers had assigned very specific start times, according to the off-peak time of the system, and/or observation of low electricity cost. Selected time, state of charges (SOC) and starting time of the EV chargers under controlled scenarios were also randomized to represent a realistic case. The EV charging data for this scenario were also incorporated into the test plan (Please see Plan Tables in Section 3.3) to be consistently applied and tested for various conditions.

The EV simulator rack 2 was also implemented in a way that smart inverter functionalities and dynamic controls through communications schemes could be tested as stand-alone or with RTDS. Several closed-loop testing were performed with power hardware in the loop to explore commanding and controls through communications.

Some of the main findings from the tests were:

- The main impact of EV charging was noted to be on the transformer current and power flow profile of the circuit. In some cases the current through transformer was tripled. The 25 kVA transformers were in danger mostly, while the larger transformers (50 kVA and 100 kVA) had more margins for accepting additional demand of the EV charging loads.

- Due to the increased loading, the voltage drop on the secondary circuits were highly observable. If the voltage on secondary circuits was very close to the lower band of the acceptable voltages, additional load of the EV chargers would reduce the voltage further beyond the acceptable range. The uncontrolled charging patterns had shown more significant impact on the voltage.

- Because the controlled charging mostly occurred during late evening time, voltage was higher at that time compare to the late afternoon or early evening. Hence, the impact on the secondary voltage drop was lower compared to the un-controlled scenarios.

- In most tested cases, there was less impact on the primary circuit voltages at 12 kV.

- Overall, it was shown that the EV simulator and the power hardware in loop test setup provided a flexible environment for various testing of EV impact on the service transformer and the primary or the secondary circuits. Different circuit arrangements or multiple customer connection points could be represented in the model and test-bed, and re-arranged to meet change in circuit characteristics or nature of the loads.